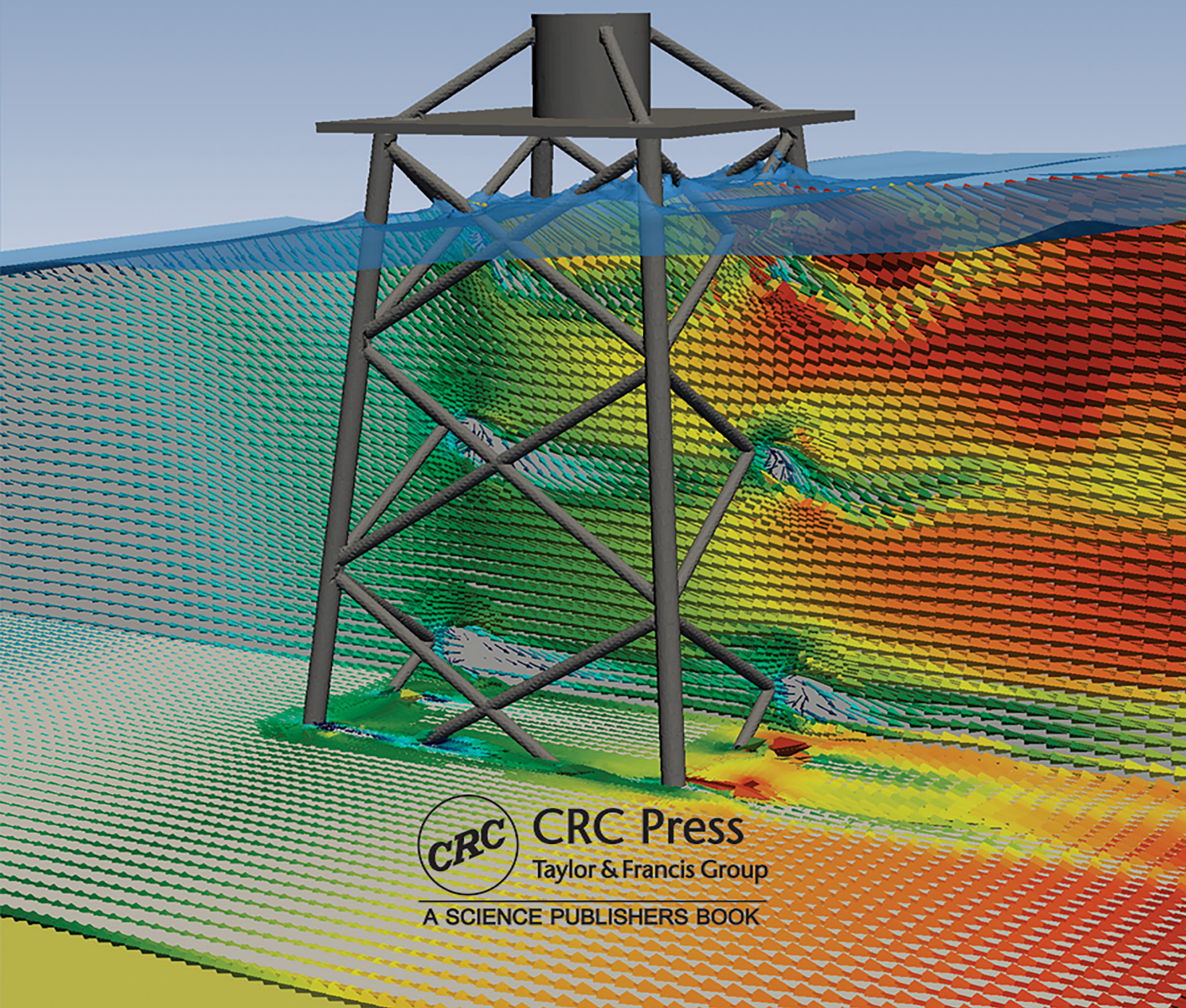
Advanced Numerical Modelling of Wave Structure Interactions

Editors

David M Kelly, Pablo Higuera Caubilla and Aggelos Dimakopoulos



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Foreword

I am not a numerical modeller myself, but over the last 30–40 years I have been an interested user of numerical models, and of their results, to help illuminate the interactions between waves and coastal structures. It is therefore as a 'customer' for numerical models of wave/structure interactions as essential complements to empirical design tools, and physical modelling, that I welcome this guidance on the developing toolkit of wave/structure numerical models, often termed Computational Fluid Dynamics (CFD).

In any discussion on the development of new tools, I am reminded that in 1847, John Scott Russell wrote to the Institution of Civil Engineers that: "*...it may be considered rather hard by the young engineer that (s)he should be left to be guided entirely by circumstances, without the aid of any one general principle for her/his assistance, ... when (s)he has to decide on a system for best opposing the force of the sea…*" Not only did numerical modelling not exist at the time, but then nor did physical modelling (until the 1930s), or even any useful analytical methods.

Over the last nearly 100 years, physical modelling of water waves and flows at structures, along coasts, and in harbours, has developed substantially, as in more recent years have numerical models, providing answers to questions that might be too complex or too extensive to model in realistic physical modelling facilities.

The authors of this book have focussed on near-structure fluid/structure interactions giving the reader descriptions of some of the latest advances, but with an emphasis on practical use of these advanced tools in solving real-world problems. But as well reviewing what is possible now, the authors have also given pointers as to how the capabilities of these tools will develop in future.

It is anticipated that this book will be of both interest and utility to engineers in consultancy as well as to researchers at MSc or PhD levels.

I very much hope that readers will find this book helpful in understanding what numerical modelling tools are available, how they work, and indeed alert you to the problems to be overcome in applying these advanced methods to real-life problems.

William Allsop

September 2020 Abingdon and Edinburgh

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Introduction

A distinguishing characteristic of anthropogenically engineered coastal environments is the highly complex interaction that exists between solid structures and the waves that impinge upon them. Similar interchanges also occur between waves and natural structures, such as reefs or rock outcrops. The interaction takes place because of the strong influence that the structure shape imposes on the hydrodynamics, which is often complex, necessarily fully three-dimensional and two-way, because of the dynamically induced movement of the structure that can result from the hydrodynamic forcing. In turn, structure motion simultaneously leads to changes in the hydrodynamics processes themselves. The problem of modelling fluid structure interactions accurately has grown in importance over the last two decades with the increasing deployment of various types of marine devices, breakwaters protecting port terminals, land reclamations and biological or natural defense solutions; all of which lie within the coastal zone.

Throughout the 1990s and early 2000s the boundary integral element method (BIEM) was used extensively, and almost exclusively, to simulate non-linear water waves and the interaction between steep waves and structures. Whilst this method has proved to be efficient for the determination of fluid-structure interaction (especially in two spatial dimensions) it is based on potential flow theory, which requires the flow to be both irrotational and inviscid. More recently, within the last 10- to 20-years, Computational Fluid Dynamics (CFD) approaches have been employed to solve the full fluid motion described by the Navier-Stokes, or Reynolds Averaged Navier-Stokes (RANS), equations incorporating a free surface (air-water interface). This type of modelling includes viscous and rotational effects and, by employing sophisticated numerical techniques, surface effects such as wave breaking (with full overturning in plunging breakers) can be simulated. Therefore, when viscous/turbulent effects and/or air entrainment effects cannot be justifiably neglected, the use of CFD models is required for meaningful simulations. The current approach is to employ the CFD model only in the immediate surroundings of the structure due to two primary limiting factors. First, the computational cost of simulating relatively large computational domains is prohibitive. Second, as a consequence of numerical (i.e., non-physical) diffusion, the majority of available CFD models cannot accurately model waves propagating over long distances (e.g., of the order of tens of kilometers).

The goal of this book is to bring together a comprehensive catalogue of state-of-the-art numerical modelling techniques for all key aspects of wave structure interaction within the coastal zone. Each of these approaches has its advantages and drawbacks, and consequently it has advocates and detractors; therefore, we aim to present an unbiased view and let each of the methods speak for themselves. A unitary approach is sought by evaluating different coastal structures subjected to a range of coastal hydrodynamics in each chapter. These vary from wave generation and propagation to the violent wave structure interaction that leads to greenwater overtopping, as well as the key problems of impulsive wave loading on, and scour around, coastal structures.

Chapter 1 addresses the state-of-the-art in numerical wave generation and absorption techniques. The chapter provides a thorough review of wave generation and absorption techniques utilized by modern CFD models. Approaches including internal generation as well as static- and moving-boundary wave generation procedures are studied critically, with the advantages and disadvantages of each technique being highlighted. Passive and active (static-and moving-boundary) wave absorption techniques, including the most recent advances, are also analyzed. The chapter ends with the discussion on future prospects for numerical wave generation.

Chapter 2 considers the use of the equations of irrotational inviscid flow coupled with CFD to produce far-field boundary conditions. This technique saves on computational time and minimizes the diffusion of wave energy, thus producing highly accurate kinematics that are used as input on the CFD solver, which models the flow close to the structure(s). In the chapter, Buldakov revives, and modernizes, a novel Lagrangian model and provides a convincing argument for the use of one-way coupling, as opposed to full coupling between models.

Chapter 3 describes wave breaking and air entrainment processes from a dual physical-numerical perspective. Lubin introduces the requisite massively parallel simulation tools, which are key to unravel the origin of complex three-dimensional turbulent structures existing under breaking waves. Special attention is paid to vortex filaments, which are only found beneath plunging breaking waves. The chapter finishes with a thorough review of existing work, focussed on discussing the gaps of knowledge and the most important challenges for future works.

In Chapter 4, Ma and coauthors consider the modelling of air compressibility and aeration effects in wave structure interaction, including important phenomena such as cavitation. In particular, the chapter considers the numerical modelling of air entrainment in breaking wave impacts on coastal and offshore structures, during which air pockets are trapped and break up to form bubbles. This study highlights that numerical modelling has the potential to produce valuable insights into these complex processes that are particularly hard to determine from experiments alone.

Chapter 5 presents a detailed description of the numerical treatment for the simulation of violent wave impacts on structures, and the associated wave loading, using the meshless smoothed particle hydrodynamics (SPH) technique. The chapter summarises some of the cutting edge research into SPH undertaken at the Italian Ship Model Basin (INSEAN) in Rome. The emphasis in this chapter is primarily on the advantage of a meshless Lagrangian method for simulating the complex free surface (air-water interface) configurations. Along with the treatment of the free surface, the requirements and effectiveness of the SPH technique in dealing with solid boundaries are also discussed.

Chapter 6 investigates the interaction of waves and porous coastal structures using a set of volume-averaged Navier-Stokes (VARANS) equations implemented in *olaFlow*, an open source model based on OpenFOAM®. The VARANS equations are derived to include gradients of porosity in both space and time to enable the simulation of moving porous media. In the first test case, RANS modelling capabilities for pre-designing structures are demonstrated by testing different alternatives to protect a breakwater against the extreme action of a tsunami-like wave. In the second application, the swash flow of a solitary wave on a beach, comprising thousands of spheres modelled with the discrete element method (DEM), is studied and compared against a smooth slope counterpart.

Chapter 7 describes the state-of-the-art in the CFD based modelling of scour around coastal structures. In the chapter, the authors detail a hybrid Eulerian-Lagrangian approach for three-phase (air-water-sediment) modelling of scour, which is implemented in a heavily modified version of the well-known interFoam solver from the OpenFOAM® package. Consideration is given over to modelling interphase momentum transfer, fluid volume exclusion and sediment packing, as well as suitable turbulence closure models within the Reynolds averaged Navier-Stokes framework. Worthy of note is that the model presented in the book chapter is able to initiate scour on an undisturbed bed for flow around a horizontal cylinder. Promising results are also presented for scour around a complex 3D gravity foundation structure.

In Chapter 8, de Lataillade and coauthors present a viable strategy for coupling fluid and solid dynamic models for modelling Fluid-Structure Interaction applications. The aim of this work is to take some bold steps towards the "holy grail" of modelling fluid structure interaction processes: a robust coupling of CFD and solid dynamic models. The target case study in this occasion concerns the simulation of moored platforms for floating wind turbines. The proposed scheme yields promising results with respect to predicting the motion of, and the forces acting upon, the moored structure.

The book concludes with an outline of selected potential future developments that have not necessarily been covered in the component chapters of the book. Principally, the chapter identifies several numerical techniques that, whilst not currently in the mainstream, appear to be extremely promising for the development of CFD in a coastal engineering framework in the short- to medium-term.

Chapter 1

Wave Generation and Absorption Techniques

Aggelos Dimakopoulos[1,*] and *Pablo Higuera*[2,*]

1 Introduction

Numerical modelling of wave propagation in the nearshore area has been around for several decades. Research work in this area has resulted in the development of a variety of theoretical and numerical methods and techniques to solve this problem. Initial efforts of modelling coastal wave propagation were performed using depth-integrated approaches, such as the Boussinesq equations (Peregrine (1967); Madsen et al. (1991); Karambas and Koutitas (1992); Nwogu (1993); Wei et al. (1995)) and the shallow water equations (Hibberd and Peregrine (1979), Kobayashi et al. (1987), Titov and Synolakis (1995)), although the latter concerned strictly shallow water wave propagation (wavelength > 20 times the water depth). Additional techniques were also developed to include flow evolution in the vertical (aligned with gravity) direction, initially by using simplified forms of mass and momentum conservation equations, e.g., potential (irrotational) flow coupled with the Boundary Element Method (Grilli et al. (1989, 2001); Belibassakis and Athanassoulis (2004)).

Models that used the Navier-Stokes equations for simulating wave propagation were also developed at about the same time, but were initially limited to 2D-vertical setups due to significant computational requirements (Johns and Jefferson (1980); Lemos (1992); Lin and Liu (1998); and Bradford (2000), among others). With the rapid improvement in computer performance during the 2000s and specially in the early 2010s, the simulation of 3D wave propagation processes using Navier-Stokes approaches became practical. Initial efforts that used three-dimensional flow domains aimed to investigate detailed turbulence structures under wave breaking with normal wave incidence (Christensen (2006); Watanabe et al. (2005)) or to simulate 3D wave transformation and breaking processes under oblique incidence (Huang et al. (2009); Dimakopoulos and Dimas (2011)).

All these early studies provided a template for establishing the concept of the numerical wave tank (NWT), i.e., a particular setup of the computational domain which allows numerical testing and performance evaluation of coastal engineering applications. These studies, nevertheless, did not yet offer a robust methodology for simulating fully developed sea states, which would allow testing realistic natural or man-made features encountered near the coast. Therefore, it was necessary to develop techniques for generating and absorbing regular and random waves at the offshore and landward boundaries in a consistent manner, in particular:

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- at the offshore boundary, simultaneous wave generation and absorption techniques allow the representation of incident wave condition which often come from a wave forecast/transformation model (e.g., SWAN, Booij et al. (1996)) and prevent re-reflections from bathymetric or man-made features; and
- at the landwards boundary, wave absorption techniques allow the complete absorption of the waves to prevent unwanted wave reflection from the outlet boundary.

To some extent, the concept of the NWT is influenced by the layout of physical modelling flumes and basins, which is based on a technology that has been mature for few decades. But, fortunately for the numerical modellers, the absence of real world limitations such as space allocation, material type and strength, and laboratory safety considerations gave rise to a diversity of wave generation and absorption techniques for NWTs that were mostly based on abstract concepts. These techniques essentially enable performing long simulations by maintaining stable and fully developed wave statistics over time and by keeping a constant water level in the NWT.

Wave generation and absorption techniques in depth-integrated models, such as the Bouss2D model (Nwogu and Demirbilek, 2001) or the FUNWAVE model (Shi et al., 2016) were implemented relatively early, as these models were generally least computationally demanding. Similar and in some ways more advanced techniques have also been developed for Navier-Stokes equations, within the context of Computational Fluid Dynamics (CFD) models. NWTs in CFD models are in a maturing process over the last 5–10 years, having as key milestones the works of Jacobsen et al. (2012) and Higuera et al. (2013). These two key publications left a significant legacy within the research community, which is summarised in the following points.

- They both demonstrated that NWTs in CFD models are capable of efficient wave absorption which was at least equal, if not better than in the laboratory.
- They both implemented the techniques in OpenFOAM®, the leading open-source toolkit for CFD applications, thus allowing the research and scientific community to replicate these results and gain confidence that these methods work.
- They presented a set of benchmarks (particularly in Higuera et al. (2013)) that can be used to compare and evaluate similar or substantially different techniques for wave generation and absorption.

The aim of this work is to present an account of the most important concepts and techniques for wave generation and absorption, such as the Dirichlet-type and radiation boundary conditions, the relaxation zone methods, internal mass/momentum source wavemakers and moving paddles. These are presented in more detail in the next section, followed with relevant advantages and disadvantages. In the last sections, an overall assessment of the existing methods is given along with ideas for future development.

2 Review of wave generation and absorption methods

In this section we will review the most important references on wave generation and absorption applied in numerical modelling. Since in most of coastal engineering cases the dynamics of interest are wave-driven, the accuracy of the wave kinematics will have a major impact in the solution, therefore, producing accurate waves starting from wave generation will minimise error propagation and second order effects. Additionally, in most cases we would like to simulate open-sea conditions, in which waves will travel away from the domain of interest.

However, since it is impractical to simulate large domains in CFD modelling, the role of the absorbing methods is to simulate the correct conditions for the wave to propagate outside of the domain, minimising the reflections.

There are several wave generation and absorption approaches that are worth mentioning, thus, this section will be split into four subsections. Taking into consideration practical space limitations, the review presented in this section is not complete, therefore, before reviewing individual techniques it is worth mentioning several recent review papers which can help the reader gather further details on wave generation and absorption methods.

The first reference worth mentioning is Schäffer and Klopman (2000), which is a classical reference in this field. Although this paper is focussed on active wave absorption for laboratory wavemakers, it has been extensively applied in numerical models afterwards, both for static and dynamic wave absorbing conditions.

The second highlighted reference is Miquel et al. (2018). In this paper different combinations of wave generation and absorption methods are tested in terms of performance (reflection coefficient) and the differences between them are reported. The model used in this work is REEF3D, and the results are compared with previous benchmarks published for OpenFOAM®.

Finally, Windt et al. (2019) is the most recent reference. This work includes an extensive assessment of all the wave generation methods available in the OpenFOAM® framework presently, considering multiple implementations of boundary conditions, relaxation zones and moving boundaries. Comparisons are made in terms of accuracy, computational requirements and features available. Differences point out that none of the methods are consistently superior in all three key performance indicators, therefore, Windt et al. (2019) can be used as a guide to select the most suitable wave generation and absorption methods for a particular problem.

2.1 Static boundary wave generation and absorption boundary conditions

Static boundary wave generation is the most straightforward technique that can be implemented in most Eulerian numerical models. In it, the theoretical expressions for free surface elevation and velocities are applied on static boundaries as fixed value (Dirichlet-type) BCs. There are numerous wave theories available with which to calculate the necessary wave kinematics, ranging from the most simple ones (Stokes first order, Stokes (1847)), only applicable to a limited range of conditions, to universal theories of high order (e.g., streamfunction, Dean (1965)) that can be used for nearly-breaking waves. The most suitable theory for a particular wave condition can be obtained with Le Méhauté (1976). Wave absorption can also be performed at the boundaries, either independently or, in some cases, simultaneously with wave generation. The most relevant wave absorption techniques are reviewed in next subsection.

2.1.1 Wave absorption boundary conditions

Probably the simplest wave absorption boundary condition is Sommerfeld radiation condition (Sommerfeld, 1964), also called wave-transmissive or open boundary condition. This technique is based on the analytical solution of radiation problems:

$$\left(\frac{\partial}{\partial t} + c^{\text{out}} \frac{\partial}{\partial x} \right) \Phi^{\text{out}} = 0 \tag{1}$$

in which c^{out} is the phase velocity and Φ^{out} is the potential of the target wave component to absorb. As noted in Dongeren and Svendsen (1997), perfect absorption can be achieved, in principle, for monochromatic waves perpendicular to the boundary and in which the wave celerity is known. Since Equation 1 is a first-order approximation, Engquist and Majda (1977) extended this BC to higher order and derived local approximations, decreasing the reflections for angles of incidence that deviate from the normal. Higdon (1986, 1987) further developed this boundary condition, introducing the incident angle in the formulation. The reader is referred to Givoli (1991); Dongeren and Svendsen (1997) for a comprehensive review of additional developments.

In this chapter we will focus only on one of the most recent advances available in literature. The work by Wellens et al. (2009) and Wellens (2012) aimed to apply open boundary conditions to real offshore problems, in which dispersive irregular wave sea states are required. Since wave components with wave celerities (c^{out}) different from the target in Equation 1 will produce noticeable reflections, Wellens (2012) proposed a rational approximation for them with the form of a digital filter (DF):

$$c^* = \sqrt{g\,h}\,\frac{a_0 + a_1\,(k\,h)^2}{1 + b_1\,(k\,h)^2} \tag{2}$$

in which a_i and b_i are the coefficients of the filter. The digital filter needs to be designed accordingly to the wave celerity range expected, with the goal of minimising the overall reflections. In this sense, Wellens (2012) recommended using the wave celerity associated to the peak spectral frequency in irregular sea states. Extensive work was performed to obtain a set of weights which achieved high performance for real cases, yielding reflections generally below 5%.

Active Wave Absorption (AWA) is another Dirichlet-type BC that can absorb waves at a boundary with minimum reflections. AWA was originally developed for laboratory wavemakers, nevertheless, it is directly applicable to numerical models, both for Dirichlet-type and moving boundaries (later introduced in Section 2.4).

The concept behind AWA is that the boundary responds actively to the incident waves, unlike passive absorption (later introduced in Section 2.2), in which damping does not change with time. In order to do so, the AWA technique requires a hydrodynamic feedback, with which to estimate the waves incident to the boundary, and react accordingly.

To study how this works we will analyse the simplest implementation of AWA, which is based on the assumption of linear wave theory in shallow waters and it has been widely applied in the literature with outstanding results. The starting point is Equation 1 in Schäffer and Klopman (2000),

$$U_c = -\sqrt{\frac{g}{h}}\,\eta \tag{3}$$

which is a very simple digital filter to calculate the velocity correction (U_c) necessary to absorb a disturbance (i.e., incident wave) of magnitude η, only depending on gravity (g), water depth (h) and η itself. The negative sign indicates that positive velocity (i.e., inflow) is required to absorb a negative elevation disturbance (i.e., wave trough), and that outflow will absorb wave crests.

Several more complex commercial implementations of AWA exist. In these, the incident-reflected wave separation is often performed via digital filters (see Antoniou (2006)) from one or several hydrodynamic feedback magnitudes measured inside the wave tank. For example, nonrecursive DF (Finite Impulse Response, FIR) involves a convolution, which introduces a time delay, whereas recursive digital filters (Infinite Impulse Response, IIR), which are composed of decaying exponentials, can be designed to be delay-free. As a result, FIR requires the hydrodynamic feedback to be collected far enough from the wavemaker to allow the system to react in time, e.g., in Christensen and Frigaard (1994) two free surface elevation gauges are placed away from the wavemaker. Alternatively, in Schäffer et al. (1994)

the hydrodynamic feedback is produced by a free surface elevation gauge mounted directly on the wavemaker paddle.

The AWA procedure is suitable to absorb not only normal long-crested waves, but also oblique waves too. This is done by splitting the boundary into smaller pieces, similar to the individual paddles of a laboratory wavemaker, each of which applies the Equation 3 independently. One of the limitations is that this procedure cannot absorb the components of the waves that propagate tangentially to the boundary which are also difficult to absorb in the laboratory.

The simple DF in Schäffer and Klopman (2000) has been applied successfully in literature (Torres-Freyermuth et al., 2007; Higuera et al., 2013; Miquel et al., 2018), and is quite effective, especially for shallow water conditions. AWA has also been applied outside the shallow water regime, with acceptable but decreasing performance as the wave conditions approach deep waters. The reflection coefficients obtained for deep water conditions are generally larger than 20%, thus not acceptable for practical simulations. This is caused by two simplifications that the shallow water conditions assume: a constant velocity profile along the water depth and non-dispersive waves ($c = \sqrt{g\,h}$), whereas in deep waters, the velocity profile decreases to almost zero throughout the water column and wave celerity is calculated by solving the general dispersion relation.

In the recent work of Higuera (2020), AWA absorption has been extended to work efficiently in deep water conditions. Two important shortcomings have been corrected by introducing wave dispersivity and vertically-varying velocity correction profiles. An additional input parameter to the model, the wave period (T), is required to calculate the precise wave celerity according to the dispersion relation. Moreover, the velocity correction profile is adapted to the depth conditions based on the general linear wave theory. Finally, a combination of AWA and passive wave absorption (relaxation zone) has been tested, indicating that each technique can benefit from the other to increase the overall wave absorption performance, as will be discussed in Section 3.

2.1.2 Examples and applications

Sommerfeld (open) boundary conditions have been widely applied in nonlinear shallow water and Boussinesq models (Israeli and Orszag, 1981; Larsen and Dancy, 1983). As Navier-Stokes equations models were introduced, Open BCs were extended to work with free surface flows via the Volume Of Fluid (VOF) technique. Examples of initial applications include the SKYLLA (van Gent et al., 1994), SOLA-VOF (Iwata et al., 1996) and the COBRAS (Lin and Liu, 1999) models. Lin and Liu (1999) report a good performance of the open BC, even for deviations of the celerity around 20%. More recently Wellens et al. (2009); Wellens (2012) have perfected the open BC in ComFLOW. Their approach is only applicable in numerical modelling, because it uses the pressure and velocities and their gradients throughout the water column as input variables, but extends the applicability of open BCs to irregular sea states.

Open boundary conditions have also been recently developed for weakly compressible SPH solvers in Verbrugghe et al. (2019), claiming that it can be extended to the incompressible SPH method too. It can be argued that this approach corresponds to a relaxation zone rather than to a boundary condition, because strictly speaking wave generation and absorption are performed in an area of buffer particles serving as ghost nodes. However, it must also be noted that these areas are much smaller (8 particles wide) than the typical lengths required in classical relaxation zone techniques, on the order of magnitude of a wavelength, therefore being closer to the application characteristics of boundary conditions.

Regarding active wave absorption, this technique was first developed based on the Sommerfeld equations in Van der Meer et al. (1993) and Sabeur et al. (1997). Later, the VOF-break model (Troch and De Rouck, 1999) was implemented for fixed boundaries, based on a commercial AWA system available for laboratory wavemakers. Some differences were introduced in the numerical model version, taking advantage of the flexibility that numerical models offer. First, the feedback was changed from free surface elevation to velocities, which are directly retrievable from the model and do not reduce the absorption performance (Hald and Frigaard, 1996). Second, arbitrarily long filters could be used because the numerical model, unlike the physical system, does not require real-time performance, thus enhancing the overall absorption rates.

A simpler system introduced in Schäffer and Klopman (2000), which does not require designing complex digital filters and only uses the free surface elevation at the wavemaker as input, was implemented and applied for the IH2VOF model in Torres-Freyermuth et al. (2010). The same approach was later extended to 3D simulations in Higuera et al. (2013) for the IHFOAM model based on OpenFOAM®. The 2D version has been implemented in the REEF3D model (Miquel et al., 2018). As mentioned before, the aim of their paper was to explore the performance of different wave generation and absorption methods and their combinations.

The limitations of this method, derived from the initial assumptions of linear waves in shallow waters, have been recently revisited and extended to work at any water depth regime in Higuera (2020). The new method, called extended range active wave absorption (ER-AWA) offers a higher overall performance and has been implemented and released in the open source *olaFlow* model (Higuera, 2017), also based on OpenFOAM®.

2.1.3 Advantages and disadvantages

Dirichlet-type wave generation presents multiple advantages. These include the simplicity of implementing them, simply as a fixed-value boundary condition, and the low computational cost of this procedure, which is often negligible and it is the lowest among the other wave generation techniques reviewed in this chapter. Nevertheless, the main drawback of this method is that it needs to be coupled with wave absorption necessarily, either at the same boundary or elsewhere. This is so because there is an imbalance between the amount of mass (water) introduced in the domain to produce a wave crest and the mass extracted to generate a wave trough. The mass differences accumulate wave by wave, producing a progressive increase of the mean water level in the domain, which needs to be absorbed (Torres-Freyermuth et al., 2007). Many wave absorption methods are suitable to deal with this effect, except for specific passive wave absorption methods which damp momentum and not mass such as momentum damping zones or dissipative beaches. As demonstrated next, AWA is the natural selection to mitigate this effect.

Regarding wave absorption, the main advantage of Sommerfeld BCs is their simplicity, which generally does not produce any significant increase in the computational cost of the model. Moreover, the absorption performance can be extremely high, provided the wave celerity and wave incidence direction is known in advance. The main disadvantages of traditional radiation conditions are that they were formulated to absorb monochromatic waves, therefore, they are not able to absorb effectively irregular (multi-chromatic) sea states. Furthermore, these techniques were conceived to work in purely absorbing boundaries rather than combined with wave generation. Nevertheless, the work by Wellens (2012) corrects these two factors.

The application of AWA in numerical models presents several advantages with respect to the laboratory systems. One convenient feature of the numerical models is the ease of obtaining flow measurements, without disturbing the flow and including variables that cannot be measured directly in the lab. New variables can provide valuable feedback for AWA systems, which by accepting additional features as input can improve their absorption performance or provide additional functionalities. For example, Troch and De Rouck (1999) uses velocities instead of free surface elevation, which are easy to obtain in the numerical model. Moreover, depth-averaged velocity components at the wavemaker boundaries were used in Higuera et al. (2013) to discriminate waves parallel and perpendicular to them, preventing spurious wave generation for non-incident waves.

Another important factor is that, AWA systems in numerical models do not require to operate in real-time, unlike AWA in laboratories. This constraint limits the complexity of the digital filters that can be applied in physical wavemakers, whereas arbitrarily complex digital filters can be used in numerical models, because they would just delay the start of the next time step calculations. The main consequence is that higher absorption performance can be achieved in numerical models, as reported in Troch and De Rouck (1999). Furthermore, eliminating the requirement of having a real-time response permits having a more flexible testing framework in which to develop new ideas.

As mentioned earlier, AWA may be required even if no incident waves to the boundary are expected, in order to prevent the increase in water level produced by the Dirichlet type wave generation. Fortunately, AWA is perfect for inhibiting such mean water level rise, which can be assimilated with a long period wave, because AWA is extremely efficient absorbing long waves. Moreover, AWA can work at the same boundary as wave generation and without significant additional computational cost. Finally, unlike the traditional radiation BCs, AWA can be applied to absorb irregular waves, not only monochromatic waves.

The main disadvantage of AWA is that it usually depends on complex digital filters, which might need to be designed ad-hoc for specific wave conditions. The simplest version of AWA (Schäffer and Klopman, 2000) presents an additional limitation, its application is typically constrained to shallow water conditions. However, the range of applicability has been extended recently in Higuera (2020).

2.2 Relaxation zones

2.2.1 Background and development

The relaxation zone method for generating and absorbing waves is an abstract method that is based on the concept of dedicating a part of the CFD model domain to perform wave generation and/or absorption. The concept can be very broadly summarised in the following equation, which, without loss of generality, is written in 1D form:

$$F(x_r) = F_b\sigma(x_r) + F_d(1 - \sigma(x_r))x_r \in [0, L_r] \tag{4}$$

where F is a model variable or parameter in broad terms (e.g., velocity, free-surface elevation, pressure, mass/momentum sink scaling parameter, numerical parameters, mesh size, among others), σ is a weighting function that ranges from 0 at the non-relaxed part to 1 at the boundary and can have various forms (e.g., linear, exponential, polynomial), x_r is the coordinate along the wave propagation axis, with $x_r = 0$ at the interface of the numerical domain and the relaxation zone, and L_r the length of the relaxation zone along the x_r-axis. Variables or terms with indices b (boundary) and d (domain), indicate that these are calculated or imposed at the boundary or the internal domain, respectively. The application of this concept in a NWT is shown in Figure 1.

In the context of wave absorption and generation problems, it has been demonstrated that an appropriate form of Equation 4 can be introduced to the flow equations (physics of the model) or the numerical solution procedure (numerics of the model) to relax the solution towards the boundary condition, within the relaxation zone domain. It has been additionally shown that given enough length, this transition becomes smooth and reflections of outgoing waves are minimised. Techniques based on Equation 4 may be referred to as "sponge layer",

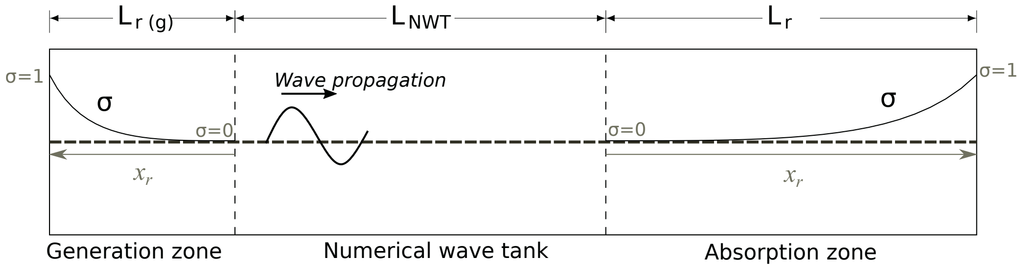

Figure 1: Illustration of relaxation zones in a NWT, according to (Jacobsen et al., 2012).

"numerical beach", "generation/absorption layers" among others. In this paper, all these techniques are considered to fall under the term "relaxation zone methods/techniques". It is worth noting that to classify as such, the relaxation zone must share an interface with the domain boundary, otherwise it falls under the internal wave maker techniques, which will be discussed in the following section.

Early work on passive absorption

Relaxation zone methods for NWTs were first applied to absorb outgoing waves at the inshore/landwards outlet, in combination with a Dirichlet boundary condition or an internal wave maker, rather than used to fully equip a NWT. In this case, the boundary condition at the outlet can be a no-slip wall (as in an actual wave tank) or a free-flow outlet (constant sea level). The purpose of the relaxation zone is to entirely dissipate the flow velocities (passive absorption) before the waves reach the outlet boundary.

The application of the relaxation zone presents a physical analogy with layouts used in the laboratory for absorbing waves such as absorbing foam, screens and beaches. In this case, the absorbing layout usually takes over few or several meters of the experimental flume or tank (as opposed to a paddle, which is the equivalent of a boundary condition in numerical models) and the absorbing layout properties (primarily the resistance it offers to the flow) are gradually increased towards the outlet wall, in a manner consistent with Equation 4. Examples of absorbing layouts in experiments can be found in Tiedeman et al. (2012) and Delafontaine (2016), among others.

An early investigation of water wave absorption using a relaxation zone was conducted by Le Méhauté (1972), by introducing an "internal friction term" in the dynamic (Bernoulli) equation of motion for the pressure, in the context of potential flow equations. The friction term is proportional to the flow potential and is broadly equivalent to a Darcy resistance term in the Navier-Stokes equations. This technique can be considered as "physical forcing" of the relaxation zone. Indeed, the physical analogy presented in Le Méhauté (1972) is parallel plates with varying density aligned with the wave direction. This may be now considered primitive, but it is consistent with the concept of increasing viscous resistance towards the outlet boundary, which is used in modern absorption techniques in the laboratory (e.g., screens, foam or beach). The concept of adding an internal friction term in a relaxation zone to facilitate wave absorption has nevertheless proven timeless, as many modern depth-integrated and CFD models still utilize this idea (Perić and Abdel-Maksoud, 2015; Dimakopoulos et al., 2019).

A generic formulation for using a sponge layer for passive absorption of waves was established by Israeli and Orszag (1981), where it was demonstrated that sponge layers, as opposed to simple radiation conditions, were capable of absorbing multiple wave frequencies.

They also demonstrated that a combination of radiation conditions and relaxation zones can optimise the absorption efficiency. Early applications of this concept can be found in depth integrated or potential flow models which matured earlier than CFD models for ocean and coastal engineering applications. In the Boussinesq model proposed by Larsen and Dancy (1983), a sponge layer method is applied by "dividing, at each timestep, the surface elevation and the flow on a few grid lines next to the boundary by a set of numbers which increase towards the boundary". In essence, they use a weighted denominator to divide the pressure and the free-surface at each timestep, right after these values are calculated by the numerical solution, and it is demonstrated that this approach efficiently absorbs outgoing waves. Their scheme is coupled with an internal source generator and it is argued that active absorption capabilities are not needed, as long as the sponge layer is introduced in all domain boundaries. The concept of introducing intermediate steps in the numerical algorithm to absorb waves, survives in many modern NWT approaches, based on CFD (e.g., in Jacobsen et al. (2012)). This concept will be hereafter mentioned as "numerical forcing", as opposed to "physical forcing" which is based on introducing appropriate source terms in the momentum equations, while preserving the original numerical solution algorithm.

Cao et al. (1993) argued that the formulation of Le Méhauté (1972) is not bounded at positive values and could sometimes result in negative dissipation, which is not desirable. Grilli et al. (1997) proposed an improved implementation of the relaxation zone technique for potential flow equations, within the context of NWTs using the Boundary Element Method (BEM). Their method included a modified dynamic free surface boundary condition for the pressure, resistant to the motion of the free surface. The influence of the modified boundary condition was increased approaching to the boundary by using polynomial weighing function with an order of 2–3. This technique was shown to achieve good absorption characteristics for short waves ($< 3\%$ reflection) achieved with a 2 wavelengths long absorption zone, but relatively poor performance for longer waves (up to 40%). This is because the modified boundary condition affected the wave kinematics close to the free-surface, thus being more appropriate for deep water waves, where the wave energy is concentrated in the upper water layers. To improve performance for longer waves, Grilli et al. (1997) combined the relaxation zone method with an absorbing piston at the outlet based on the Sommerfeld equation, which is known to yield good absorption performance for longer, shallower waves. The relaxation zone approach proposed by Grilli et al. (1997), without radiation conditions, was adopted for a NWT based on a single phase Navier-Stokes model with a moving free-surface boundary in Dimas and Dimakopoulos (2009), where good performance was achieved, for intermediate waves, with a 4 wavelengths long relaxation zone.

The application of the relaxation zone method for passive absorption was also further elaborated in Boussinesq modelling by adding linear resistance terms in the momentum equations (Kirby et al., 1998). A step further was taken in Nwogu and Demirbilek (2001), by adding a linear mass sink term. Whilst this term interferes with mass conservation, Nwogu and Demirbilek (2001) recommend its inclusion, arguing that it further enhances absorption performance. This is the physical equivalent of, e.g., adding appropriate overflow arrangements in a numerical wave tank, with the overflow level reaching the mean water level as the onshore boundary is approached.

A relaxation zone method for wave absorption in CFD models was proposed by various researchers, starting from the late 90's. Mayer et al. (1998) used a "numerical forcing" approach which relaxes the free surface elevation and velocities to prescribed values at each time-step, using a 3rd order polynomial equation for σ. Note that a fractional time-step scheme with pressure correction is employed for solving the Navier-Stokes equations. Whilst Mayer et al. (1998) do not report the absorption efficiency, they demonstrate a good overall comparison with analytical solutions and experimental data, including structures interacting with waves and currents. The COBRAS model (Lin and Liu, 1999) also employed the formulation of the Israeli and Orszag (1981) approach, coupled with an internal source wave maker, and has since been used for numerous applications during the late 90's and 00's (see section on internal wave makers below).

Early work primarily comprised passive absorption schemes, while wave generation was mostly achieved by using internal wave makers. More recently, CFD-based NWTs were developed by fully utilising the relaxation zone method, once this concept was demonstrated to be capable of simultaneously absorbing and generating waves at the boundary Jacobsen et al. (2012). This process has the same result as the concept of the active wave/generation absorption applied to absorbing boundary conditions and numerical wave paddles, but strictly speaking, it cannot be described as active, as the relaxation zone method does not adapt to the local wave properties. In order to distinguish between the two, the term "simultaneous wave absorption and generation" (SWAG) is hereafter used in the context of using relaxation zone method for both wave generation and absorption.

Simultaneous wave absorption and generation

The conversion of the passive absorption zone techniques presented above to SWAG techniques are—in hindsight—relatively straightforward, particularly for the ones that rely on the notion of dissipating waves by forcing the solution to constant or zero target velocity and free surface elevation values. The generation can be achieved by introducing a target velocity or free surface that corresponds to a wave theory. An early demonstration of this idea was performed by Afshar (2010) who, in terms of classification, stands between the relaxation zone and the internal wavemaker concept (see Figure 2). A layout with three relaxation zones is proposed, with the first two located at the offshore/generation boundary (Zone I and Zone II) for "ramping up" and "ramping down" the wave field. A third relaxation zone (Zone III) is introduced at the outlet for wave absorption. Generation and outlet boundaries were considered as solid walls, and in this sense, the overall scheme approaches the idea of an internal wave maker. Pressure, velocities and volume fractions were relaxed with 3rd and 6th order functions, using "numerical forcing". Zone I and II were one wavelength long while Zone III was two wavelengths. The method was tested for linear, standing and nonlinear waves and was demonstrated to be successful at a conceptual level. Several areas of improvements were identified, including the interpolation of forcing terms between cell centres to avoid the appearance of a saw-tooth profile in generation zones and the removal of high air velocities in the relaxation zone.

Jacobsen et al. (2012) devised the waves2Foam library which was written for the OpenFOAM® platform and was fully based on the relaxation zone method, as the relaxation zone concept was combined with a Dirichlet condition for wave generation at the offshore boundary, as in Figure 1. A substantial improvement was achieved over the early concept

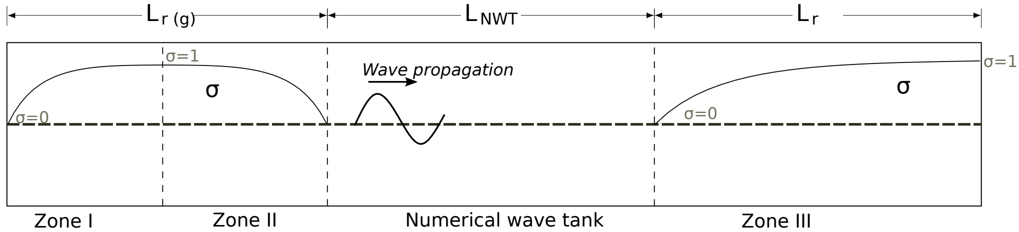

Figure 2: Illustration of relaxation zone from Afshar (2010).

of Afshar (2010). The proposed technique addressed the interpolation issues by projecting the location of the free-surface in a boundary face or a computational cell and calculating the water fraction based on the interpolated volumes. Air velocities were forced to zero through the relaxation zone technique, and pressure forcing was made redundant. The relaxation function had an exponential form, following recommendations from Mayer et al. (1998). The method was shown to be able to efficiently generate and absorb waves of linear and nonlinear regimes with high efficiency, as wave reflections were $< 3\%$ for linear and nonlinear waves and relaxation zone length of two wavelengths.

This idea was largely successful and was picked up and further developed by the research community. Dimakopoulos et al. (2016) verified a similar level of reflection efficiency by testing the waves2Foam library against regular wave conditions proposed by Higuera et al. (2013). In addition, they further demonstrated the capability of the toolkit as a SWAG scheme for generating regular, random, directional waves, with or without currents. The capability of the scheme to simultaneously absorb regular and random waves was demonstrated through numerical tests of wave reflection against solid walls. The evolution of wave height of standing regular and random waves was compared against analytical solutions and agreement was excellent for low-steepness waves. It was also further demonstrated that the method is capable of performing well within the context of a 3D numerical basin, showing a good performance for generating short-crested waves, as well as wave and current interaction in oblique directions.

The relaxation zone technique of Jacobsen et al. (2012), is also adapted to the Reef3D model (Miquel et al., 2018), and includes numerical forcing of the dynamic pressures. Their implementation proved to be highly efficient for random waves absorption ($< 2\%$) and less efficient for regular waves ($< 10\%$), something that seems counter-intuitive and contradicts findings from Jacobsen et al. (2012) and Dimakopoulos et al. (2016). It should nevertheless be noted that the implementation of the method in Reef3D includes relaxation of the pressure terms and the reflection analysis that they use is more likely to be suitable for random rather than regular waves, so this may justify the different findings. Additional models that use the relaxation zone approach are the OpenFOAM®-based toolkit Naval Hydro pack (Jasak et al., 2015) or Star-CCM CFD platform (Perić et al., 2018).

As the relaxation zone technique became increasingly widespread, further analysis was performed regarding the parameters relating to the relaxation zone. Perić and Abdel-Maksoud (2016) used mass and momentum sources by setting $F_b = F_s \sigma(x)(f - f_t)$ and $F_d = 0$ in Equation 4, where f, f_t are the calculated and target flow variables (volume of fluid or velocity) and F_s is a scaling coefficient. Their analysis showed that F_s should be proportional to the wave frequency while the length of the relaxation zone should be proportional to the wave length for the absorption zone to achieve relaxing capabilities. In addition, they demonstrated that the optimal values of these parameters are $F = \pi\omega$ and $x = 2\lambda$ for an exponential type relaxation function. Similar values were consistently used by researchers using trial and error approaches, e.g., see Nwogu and Demirbilek (2001) or Jacobsen et al. (2012). In Perić and Abdel-Maksoud (2018), a theory was developed to predict reflection coefficients for monochromatic waves, given the parameters of the relaxation zone. The theory was found to agree with numerical tests and the researchers or engineers can use it for selecting appropriate parameters for the relaxation zone conditions, given a target reflection coefficient. The authors nevertheless recommend further work on extending the theory to cover irregular or random waves.

In Dimakopoulos et al. (2019), a relaxation zone technique is proposed, which is very similar to the one presented in Perić and Abdel-Maksoud (2016). Dimensional analysis confirms findings from Perić and Abdel-Maksoud (2016) that the scaling factor F_s must be proportional to the wave frequency to achieve good performance and the value of the scaling coefficient is set to 5 times the angular wave frequency, following recommendations from Nwogu and Demirbilek (2001). The method is implemented in the CFD toolkit Proteus (Kees et al., 2011), showing good performance for generating and absorbing random waves, although the approach can be possibly improved by modifying the mass conservation equation, as the method only considers momentum sources.

2.2.2 Examples and applications

The relaxation zone method for CFD models became widespread after the release of the waves2Foam library and it is usually combined with the OpenFOAM® CFD toolkit. The method proposed by Jacobsen et al. (2012) has been used for a wide range of applications, including modelling wave structure interaction processes in seawalls and breakwaters (Richardson et al., 2014; Jensen et al., 2014; Medina-Lopez et al., 2015; Hu et al., 2016; Jensen et al., 2017), marine and offshore structures (Palm et al., 2013; Fuhrman et al., 2014; Eskilsson et al., 2015; Jasak et al., 2015; Moradi et al., 2016; Vyzikas et al., 2017; Chen and Christensen, 2018), naval and ship hydrodynamics (Piro, 2013; Windén et al., 2014; Shen and Korpus, 2015; Vukčević et al., 2017; Kim and Lee, 2017; Liu et al., 2018) and soil, sediment and scour processes (Stahlmann and Schlurmann, 2012; Jacobsen and Fredsoe, 2014; Karagiannis et al., 2016; Cheng et al., 2017; Elsafti and Oumeraci, 2017). The list is not exhaustive as many more researchers and engineers have used the relaxation zone method in the context of the OpenFOAM® CFD toolkit.

The relaxation zone method has been also used for modelling engineering applications in the coastal and marine environments in other models as well, such as the Reef3D model (Bihs et al., 2015; Chella et al., 2015; Kamath et al., 2016; Ong et al., 2017)) and the Proteus CFD toolkit (Cozzuto et al., 2019; de Lataillade et al., 2017; Mattis et al., 2018), covering a broad range of applications, similar to the one listed for OpenFOAM®.

2.2.3 Advantages and disadvantages

The main advantage of the relaxation zone method is primarily the high fidelity of wave generation along with high efficiency in absorption. This is because the method is not susceptible to boundary instabilities due to the sudden change of flow equations, while forcing analytical solutions or linear approximations meaning that evanescent modes and parasitic waves (typical in moving paddles or internal wave makers) are not present or very quickly dissipated.

Another advantage is the ease of implementation. It is relatively straightforward to add source terms to existing equations or to use “numerical forcing”, without particular considerations for numerical stability and accuracy, as opposed to, e.g., radiation boundary conditions. For example, the method used in (Dimakopoulos et al., 2019) performed a simple adaptation of the Darcy term in the porous media equation to implement SWAG. This method is therefore suitable to implement in newly and/or rapidly developed models, where for example an adaptation of an existing model component may allow the model to be used as a NWT. The inclusion of the mass source term through the volume of fluid scheme may require some treatment to, e.g., avoid non-physical oscillations at the generation zone (Afshar, 2010; Jacobsen et al., 2012). Whilst this may require some additional efforts, including mass sources is recommended, as it has been reported that it enhances absorption (Nwogu and Demirbilek, 2001) and it is also capable of maintaining the water level in the domain constant, thus not needing corrections for influx due to a mass imbalance between generation of wave troughs and crests.

The relaxation zone also needs a suitable selection of parameters such as relaxation function, length and scaling of the coefficient, thus being subject to uncertainties. Recent research and engineering practice have addressed these issues. Based on the literature consensus, the authors recommend the following:

- Length of generation zone: $L_r \simeq \lambda$ (corresponding to peak frequency for random waves)
- Length of absorption zone: $L_r \simeq 2\lambda$ (corresponding to peak frequency for random waves)
- Scaling parameter: F_s=3-5 ω
- Relaxation function: $\sigma = \frac{\exp^{x_r/L_r} - 1}{\exp^1 - 1}$.

Some of these values are theoretically proven (see Perić and Abdel-Maksoud (2015) for regular waves. For the remaining parameters or wave regimes, these recommendations are demonstrated to have a reasonable performance throughout multiple studies in literature. Note that frequency and wavelength parameters correspond to peak frequency and wavelength for random wave regimes.

Undoubtedly the greatest disadvantage of the method is the additional computational resources required for running engineering applications, compared to other methods presented in this article. Regarding wave absorption, the domain must be extended by about two wavelengths and this can significantly increase the length of the domain. Perić et al. (2018) also demonstrated that a careful selection of the relaxation zone parameters may allow for a reduction of the size of the absorption zone, e.g., using 0.5–1 wavelenghts, rather than two. (Dimakopoulos et al., 2016) have demonstrated that increasing the mesh size with a mesh progression ratio of 10%, the mesh cells in the absorption zone can be reduced by $> 95\%$, whilst maintaining equal or better absorption efficiency. A similar technique can be applied in unstructured meshes (de Lataillade, 2019). The caveat of this approach is that the free surface tracking scheme should be robust enough in order to cope with changes in mesh size along the free surface without introducing spurious oscillations.

Dedicating up to a wavelength for SWAG cannot essentially be considered as an increase of the computational domain, as for all generation methods, it is considered good practice to leave a buffer zone after the generation boundary to allow the waves to develop before entering the main domain (e.g., approaching a slope or a structure). In this case, the role of the buffer zone can be played by the generation zone. It was nevertheless demonstrated by Dimakopoulos et al. (2016) that the computational cost associated with generating non-repeating random wave sequences for, e.g., simulating a storm event may be disproportionate to the overall cost of the simulation. For example, in Dimakopoulos et al. (2016), it was demonstrated that using 500 wave components for generating a random wave series which corresponds to 250 non-repeating waves doubles the simulation time in a NWT of 240,000 mesh cells, when compared to simulations that use 50 components. This is primarily due to the fact that trigonometric and hyperbolic functions are rather expensive to calculate for each cell and each time step in the relaxation zone.

Several approaches have been proposed to address this problem. Dimakopoulos et al. (2016) showed that by replacing native C++ and FORTRAN trigonometric functions with 4th order Taylor approximations results in a reduction of the computational cost by an order of magnitude, whilst the approximation errors remained $< 1\%$. This reduced the overall cost but it did not completely eliminate it, e.g., simulations with 500 components in the NWT mentioned before need 1.4 more times, rather than double with the native functions. In Jacobsen (2017) a stretched distribution of the spectrum is proposed for improving non-repeatability of the series, thus needing less wave components for describing a full storm, but this approach does not offer a consistent discretisation of the spectra in the frequency range away from the peak. Similarly the computational time in Jacobsen (2017) may be further reduced by manipulating the trigonometric and hyperbolic functions to split spatial and temporal terms, storing spatial terms in memory and only calculating temporal terms during time advancement. This has demonstrated to speed up the calculation time needed to compute the signal by 50 times for 1000 wave components. More recently, Dimakopoulos et al. (2019) developed a method based on pre-processing the random wave signal using spectral window decomposition methods. Their technique was demonstrated to be able to generate non-repeating signals of $\mathcal{O}(1000)$ waves, size using $\mathcal{O}(10)$ frequency components, thus achieving similar reductions in computational cost. The technique was tested in the CFD toolkit Proteus.

Overall, the relaxation zone is an accurate and easy technique to implement for generating and absorbing all wave regimes, but the method is indeed computationally expensive. For its merits, thhe relaxation zone is one of the most preferred methods to use in NWT and researchers have been making significant advances in addressing its drawbacks relating to speed. Including these advances in future works will further increase the attractiveness of the technique.

2.3 Internal wave makers

2.3.1 Background and development

The Internal wave maker (IWM) concept is usually implemented by creating a generation line or area inside the domain and adding source terms to the mass or momentum equations to generate waves. This area is expected to be transparent to the wave propagation (i.e., does not reflect waves), therefore, full wave absorption can be achieved as long as passive absorption zones or absorbing boundary conditions are added to inlet/outlet boundaries.

Originally, Larsen and Dancy (1983) proposed an internal generation scheme that is based on adding to or removing some volume of water from the domain by modifying the mass equation of the Boussinesq approach. The source terms were implemented after the equations had been discretised ("numerical forcing"). In their work it was demonstrated that the IWM remained transparent to the propagation of nonlinear regular waves. The proposed implementation was rather rudimentary and required tuning its performance on a case-by-case basis (Wei et al., 1999). It was also demonstrated that it was not suitable for more advanced formulations of the Boussinesq problems (Nwogu, 1993; Wei and Kirby, 1995). The overall concept was nevertheless relatively successful as it was the starting point for further improvements and adaptations in Boussinesq and CFD models.

Wei et al. (1999) proposed a new formulation for IWM, comprising the addition of source functions in the momentum and mass equations before these are discretised ("physical forcing"). The source function is relaxed over a region by using a bell-shaped distribution, rather than being a point source. It seems that the source functions parameters (amplitude, width) require tuning/calibrating against the target wave characteristics. The concept is shown to be transparent to the wave field, as reflected waves can propagate to the other side of the IWM and absorbed at an offshore absorption zone. The physical analogy of this implementation is to use a perforated internal wave maker in a flume/basin, but it is evident that such a concept may be not be fully realisable in a laboratory setting.

In CFD models, Lin and Liu (1999) applied an IWM to their VOF-based model, initiating the concept of a NWT for 2DV numerical flumes. The approach uses a relatively concise source region which is placed internally in the flume and below the free surface. In this region, the continuity equation is locally modified to include inflow and outflow fluxes that cause wave excitation. These terms subsequently drive the momentum equation towards wave generation through the pressure-velocity coupling scheme. The mass source functions

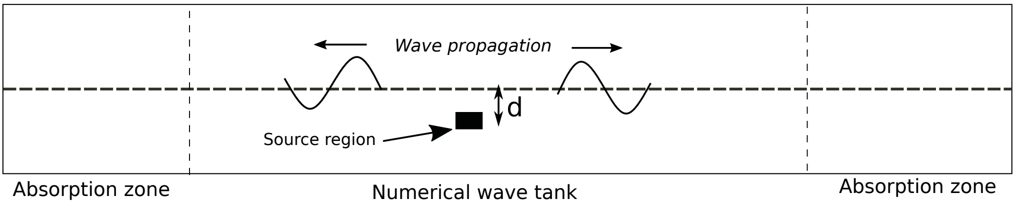

Figure 3: Illustration of internal wave maker in a NWT according to Lin and Liu (1999).

for a monochromatic wave have the following form:

$$s(t) = \frac{cH}{A} \cos(\omega t + \phi) \quad (5)$$

where ω, H and c is the wave angular frequency, wave height and celerity, respectively, and A is the area of the IWM. The concept can be extended to cover higher order waves, as well as random and directional waves, by linear superimposition of components. A sketch of the concept used by Lin and Liu (1999) is shown in Figure 3. The physical equivalent of this layout would be installing a submerged outlet in an laboratory wave basin and forcing oscillatory discharge to generate waves. Lin and Liu (1999) performed numerical tests with a rectangular source area placed in the middle of the flume, and absorbing (radiation) boundary conditions at the sides. Their approach performed relatively well for the wave regimes tested, including nonlinear and random waves. It was nevertheless found that the position and size of the source area greatly affects the wave generation performance. It was further demonstrated that the optimal location was at about 1/4–1/5 of the depth below the surface and the optimal size was $< 5\%$ of the wavelength, meaning that both the size and location of the source wave maker may have to be optimised depending on the wave conditions. The concept was extensively used in the COBRAS model, in tandem with both absorbing (radiation) boundaries, and relaxation zones for passive absorption (see relevant section). This approach was later proposed for establishing a NWT within the PHOENICS finite element model (Hafsia et al., 2009).

Saincher and Banerjee (2017) further assessed the performance of Lin and Liu (1999) IWM for steep waves in deep, intermediate and shallow waters by placing an IWM in the middle of the tank and using absorption zones at the sides to dissipate outgoing waves. They concluded that steep waves generated in deep or shallow waters may experience excessive wave height damping. It is argued that wave height dissipation is caused by vortices generated by the IWM. In deep water waves, the arrival of these vortices to the free surface was associated with wave height dampening (possibly through artificial incipient breaking), and it was noted that the problem was solved by adjusting the location of the IWM towards deeper water and increasing the size of the source area to reduce velocities. Due to the change of location and size of the IWM, additional calibration of the IWM had to be performed. Using a larger IWM to counter vorticity generated by the local flow gradients developed in IWM similar to the ones proposed in Lin and Liu (1999) was originally conceived by Perić and Abdel-Maksoud (2015) to facilitate deep water wave generation. For shallow water waves, relocating the source to lower depths was not particularly effective, so the authors proposed to increase the source size to cover the full water depth. This modification yielded good results, although it can be argued that this method is converging to the one proposed by Wei et al. (1999), as the source area is extending throughout the whole water column.

Choi and Yoon (2009) developed a concept for a momentum source based IWM in ANSYS Fluent. In their model, they adapted the methodology proposed by Wei et al. (1999),

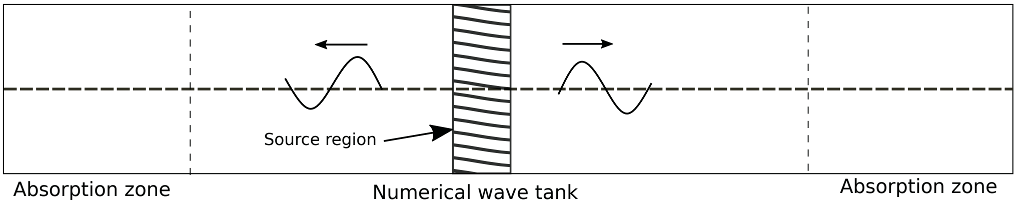

Figure 4: Illustration of internal wave maker in a NWT according to Choi and Yoon (2009).

for application in CFD models and developed a 3D numerical wave tank with capability of generating plane and directional waves. The formulation of the source terms included in the Navier-Stokes equations can be summarised in the following equation:

$$\begin{aligned} S_x &= -2\beta x g \exp -\beta x^2 \frac{D}{\omega} \sin\left(k_y y - \omega t\right) \\ S_y &= g \exp -\beta x^2 \frac{D}{\omega} \sin\left(k_y y - \omega t\right) \end{aligned} \tag{6}$$

where x, y are coordinates in the propagation plane, along and perpendicular to the main wave direction, respectively, g is the gravitational acceleration, β is a coefficient depending on the width of the generation area and the wavelength and k_y and ω are the wavenumber on the vertical (y) axis and angular frequency of the waves, respectively. The concept can be extended to cover higher order waves, as well as random and directional waves, by linear superimposition of components. A sketch of the numerical flume set-up can be shown in Figure 4.

The formulation in Choi and Yoon (2009) did not include the variation of the source terms over the vertical axis as in Wei et al. (1999), since it was found that this did not significantly affect performance. During numerical tests of 2D and 3D regular wave propagation, satisfactory agreement was demonstrated against physical modelling results, analytical solutions and bechmark cases previously simulated by Lin and Liu (1999) model. Choi and Yoon (2009) also observed that the influence of evanescent modes due to the vertical profile at the IWM is limited to a distance of 2–3 water depths from the IWM, however this was observed for intermediate to shallow wave conditions, where the assumption of constant velocity over the depth has some validity, as opposed to deep water waves.

Ha et al. (2013) further improved the approach proposed by Choi and Yoon (2009), by implementing it in the NEWTANK model. They argued that the use of both momentum and mass source in the Navier-Stokes equations improved generation performance. They also note that the method has limitations for generating deep water waves, given that it has been originally developed for Boussinesq equations. The IWM was coupled with passive absorption layers and numerical tests of random and multi-directional waves were performed, showing overall good performance for intermediate and shallow waves, but not for deep water waves. It could be nevertheless argued that the latter might have been because they used a relatively coarse mesh, as their results demonstrate that the wave height is correctly generated at the IWM location but quickly dissipates during propagation in the NWT.

Liu et al. (2015) implemented the IWM concept of Choi and Yoon (2009) in the framework of an Incompressible Smoothed Particle Dynamics (ISPH) model (particle-based Langrangian method). They do not use mass source terms, as these would require adding and removing SPH particles from the domain thus causing difficulties and complications for numerical implementation and stability. They observed that the optimal width of the source region is about 20%–50% of the wavelength and that a buffer zone is required to allow the