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COMPOSITE MODELLING: COMBINING PHYSICAL AND NUMERICAL MODELS

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Abstract
The paper presents an overview of composite modelling, defined as the joint use of physical and numerical models, within the hydraulic modelling community. It draws on work undertaken within the research project Hydralab (www.hydralab.eu) and subsequently in an IAHR working group on Composite Modelling. The strengths and weaknesses of physical and numerical models are analysed, along with selected case studies that focused on the methodologies used and their impact on the modelling approach. Some reflections on key elements in composite modelling will be presented. Composite modelling is still in its infancy in the hydraulic community, but there is a growing trend towards using both numerical and physical models together. The subject will be developed by the sharing of experience and the development of standards.

1 Introduction

Hydraulic studies have been traditionally undertaken with physical models, which reproduce flow phenomena at reduced scale with dynamic similarity. Today, numerical models are increasingly being used in place of physical models. These models rely on mathematical descriptions of complex turbulent processes and boundary conditions but can be cheap and versatile. Physical and numerical models both have their strengths and weaknesses (van Os *et al*, 2004) and their merits must be compared to the benefits of theoretical analysis (desk studies) and measurements made in the field.

A single tool cannot adequately reproduce the complex processes involved in many hydraulic problems and thus replace all the others. Combining tools can add value, but also cost. The combined use of numerical and physical models to address a problem is called composite modeling here. Although there has been a debate over the definition (as summarized in Gerritsen *et al*, 2009 and Gerritsen and Sutherland, 2011) and particularly over what the difference is between hybrid modeling and composite modeling, this paper considers all aspects of how to address a problem using physical and numerical models in an integrated and balanced way as composite modeling.

Physical and numerical models both have limitations that can restrict their independent use. Composite modelling can lead to different forms of improvements: being able to model problems that cannot be modelled by either physical or numerical modelling alone; increasing quality at the same cost or obtaining the same quality at reduced cost, reducing uncertainty at the same cost and realising that uncertainty reduction is also a quality issue. Composite modelling in the field of coastal and hydraulic modelling is a rather new approach, and relatively little has been published in the literature. However, when researchers understand the benefits and limitations of each technique, they can develop a research plan that utilizes composite modeling to increase the the efficiency and effectiveness of the modeling process.

This paper summarises the strengths and limitations of physical and numerical models in Section 2. Then in Section 3 a selection of composite modeling approaches that are in use are described, drawing on the experience of those in the EU-funded research project HYDRALAB (www.hydralab.eu) and the subsequent and ongoing IAHR working group on composite modeling. The final section then describes common themes and challenges for future developments.

2 Strengths and weaknesses of physical and numerical models

Section 2 describes the perceived strengths and weaknesses of physical and numerical models, through the use of a SWOT analysis, which outlines the internal strengths and weaknesses of each model type, but also highlights external opportunities and threats.

2.1 SWOT analysis of physical models

2.1.1 Strengths of physical models

- Natural reproduction of complex nonlinear physical phenomena that are not fully understood, such as: breaking wave impact forces on structures, overtopping, hydraulic jumps, separation zones, vortex formation and poor energy dissipation. These problems are often immediately apparent in a physical model;
- Multiple flow rates or wave conditions can be tested in a very short time; so for example, any hysteresis effects caused by a varying flood hydrograph can be investigated quickly;
- Small changes to structure or bathymetry are often quick to implement and test;
- Well-established with a long tradition, so trusted;
- Considered as the gold standard for many modeling problems.

2.1.2 Weaknesses of physical models

- Scale effects. Scaling criteria include Froude, Reynolds, Webber, Cauchy and they cannot all be satisfied at once.
- Model effects, such as the generation of spurious reflections from boundaries.
- Physical models can be costly and time consuming to construct and to make significant adjustments;
- Extracting data can be difficult. It can be difficult to make detailed pressure measurements, for example. Moreover, many instruments measure at a single point and multiple repetitions are needed to provide the required coverage.
- Best results come from experienced modelers who understand the background and theory.
- Models are often destroyed after testing and analysis (so it is costly to return to a study);
- Require a large area and dedicated facilities.

2.1.3 Opportunities for physical models

- Development of sensor technology to measure distributed time series, such as time series of measurements along a line, in a plane or over a 3D volume. Such instruments are being developed using optical and acoustic technology (for example within HYDRALAB);
- Development of computer power and data-handling capabilities;
- The construction of a limited number of large-scale truly international facilities would allow key studies to be done with limited scale effects, from which smaller studies could be benchmarked;
- The development of composite modeling to get the best from physical and numerical models.

2.1.4 Threats to physical models

- Numerical models have rightfully replaced physical models in some areas, such as tidal flow modeling and this trend will continue;
- The emergence of CFD code, which typically solve the Reynolds-averaged Navier-Stokes equations using a variety of approaches. CFD modeling has extended the areas where numerical models may be applied;
- There is an almost unswerving acceptance of numerical model results that is becoming noticeable in many who have never conducted a physical model test series.

2.2 SWOT analysis of numerical models

2.2.1 Strengths of numerical models

- Adequate representation of many physical processes. Peer-reviewed papers have validated the use of numerical models to model free surface flow for many different applications especially for subcritical flows;
- Can run many configurations and options;
- Data can be extracted from any point in the model at any time;
- Can return to a model months or even years later to repeat or extend a study at low cost (although there are often issues when hardware and / or software changes);
- Do not suffer from scale effects in the same way as physical models;
- Can be operated anywhere (except when high performance computing required).

2.2.2 Weaknesses of numerical models

- Numerical modeling is often constrained by gridding/computational time for models with large spatial and/or time domains. This may require a 2D approach instead of a full 3D model;
- Many processes are represented by parameterizations of observed results from physical models, with restricted ranges of applicability;
- There are always sub-grid or minor processes that cannot be represented;
- Incorrect or improperly applied gridding techniques have the potential to introduce numerical errors;
- Alternative settings give different results. Primary inputs include defining the boundary conditions, the turbulence model and its parameters, model roughness and the numerical approach for solving the equations (implicit versus explicit, 1st 2nd or 3rd-order etc.). Some parameters such as the boundary conditions are critical for properly simulating prototype conditions. Other parameters provide more subtle changes. Understanding the effect of the various methods, approaches and parameters are crucial in making sure that the model represents the true physical flow;
- The number of runs required to evaluate the routing of a hydrograph (for example) will be very time consuming for a numerical study. Similarly, simulating the routing of a complete hydrograph can require simulation times that are unrealistic.
- A numerical model is limited in its ability to analyze the hydraulic stability and effect of unsteady flow downstream of a control structure;
- Best results come from experienced modelers who understand the background and theory.

2.2.3 Opportunities for numerical models

- Increasing computer power means larger and larger problems are being tackled.
- Continued supply of high quality datasets from physical models (and field observations) with limited or known scale effects will support the development and validation of numerical models;

- The development of composite modeling to get the best from physical and numerical models.

2.2.4 Threats to numerical models

- The development of numerical modeling would be threatened by the demise of physical modeling (were that ever to happen).

2.3 Summary of SWOT analysis

The results from the SWOT analysis indicate that both physical and numerical models are developing and improving. Numerical models still rely in physical models for their development and yet their strengths are often complementary. The development of composite modeling techniques should help to improve the results that can be obtained from physical and numerical models by utilizing the strengths of each.

2.4 Limits to assessment of strengths and weaknesses

It is difficult to express the strengths (or weaknesses) of the models in quantifiable ways. Judgments of model strengths (and indeed of which model type is the best or most appropriate) are not normally quantified. Moves towards the quantification judgment of models and away from the normal subjective judgment of models are based on the development of skill scores (Sutherland *et al*, 2004) and other statistical measures of model performance.

The model that provides the greatest level of predictive skill should be used, but in order to determine model skill the predictions must be compared to the correct answer. There are many situations that can be modeled with physical and numerical models where neither answer is free from error and in these circumstances it is difficult to calculate model skill and hence to determine which approach to take in a quantifiable manner.

An example of the difficulty in quantifying model skill was provided by Sutherland and Obhrai (2009) (summarized in Gerritsen *et a*l, 2009, Gerritsen and Sutherland, 2011) in the modeling of beach development (including scour and erosion) around a set of detached offshore breakwaters. The hypothesis tested was that a quantitative technique for optimising the information flow between models could be developed using skill scores (Sutherland *et al*, 2004). The skill scores were intended to give a quantitative measure of the incremental benefits of adding additional processes or using more complicated boundary conditions (Sutherland and Obhrai, 2009). However the physical model and the numerical model both have strengths and weaknesses, so neither gives the correct bathymetry needed to calculate a skill score (Sutherland *et al*, 2004). A subjective analysis of strengths and weaknesses was undertaken which allowed the authors to choose a limited area of the models where the physical model was judged to give the best results. This model was used as the 'correct' bathymetry and skill scores relative to it were obtained. The move away from subjective judgment of model quality (or skill) towards objective judgment was therefore compromised.

Moves to establish methods for assessing model performance should be encouraged as should the development of databases that could be used to assess model skill. An approach to developing databases that allow the strengths and weaknesses of physical and numerical models to be assessed in a quantified way is to conduct the same experiment at large scale and at smaller scales to allow the differences to be compared. Sanchez-Arcilla *et al* (2009) have attempted this with wave flume tests of beach erosion and accretion at three different scales, while Lemos *et al* (2009) (summarized in Gerritsen *et al*, 2009, Gerritsen and Sutherland, 2011) have attempted something similar with wave propagation and cross-shore sediment transport. Both papers report differences which could lead to a better understanding of scale effects and eventually to a quantified assessment of uncertainty in model studies.

3 Composite modeling approaches

A selection of composite modeling approaches are described below.

3.1 Model nesting

Model nesting is the most commonly applied and traditional method of linking numerical and physical models. A global or regional numerical model provides the external boundary conditions for a smaller area, more detailed model. Model nesting is a common way to downscale numerical model results from the global to the local level or to drive a more detailed regional model from a less detailed, larger scale model. However, here we are interested in how to drive a physical model covering a small, specific area, from a numerical model of a wider area.

In a coastal area where a breakwater is being built, for example, it may be necessary to construct a physical model to test armour stability, scour, overtopping or any other nonlinear phenomenon that cannot accurately be represented in a numerical model. In this case an offshore wave condition would typically be obtained and a regional wave model used to propagate the desired wave conditions inshore, modelling processes such as shoaling, refraction and possibly diffraction. The modelled wave condition is output at typically one location in relatively deep water at the offshore edge of the physical model. A characteristic wave height and wave period (often the significant wave height and peak wave period) is extracted from the numerical model, even if it is a spectral model with wave-wave interactions that contains much more information than simply height and period. A wavemaker will then generate an irregular but normally long-crested sea state with a standard spectral shape.

Similarly, prior to the construction of a physical model of a hydraulic structure such as a dam, a river system may be modeled using 1D model or a combination of 1D and 2D models. Hydrographs from these models may be used as inputs to a more detailed 2D or 3D model of the local area around a hydraulic model (or may be used as the boundary conditions for the model). Successive models represent smaller areas and probably smaller timescales in more and more details.

Mesting is an extremely well established technique, which has evolved over the years as technical capabilities have expanded.

3.1.1 Potential improvements to nesting techniques

Nesting tends to involve the transfer of a simple representation of the conditions at the model boundary. For wave model studies, as discussed above, wave conditions may vary across the offshore boundary and the development of wavemaker technology to represent spatially-varying input conditions is to be expected. Other efforts could be made to transfer more information from the (numerically) model to the physical model. Information is not normally passed back to the regional model from the local one.

3.2 Design of physical models

Many physical models are designed with the assistance of numerical models. Examples include:

- Coastal area numerical model set up to model a wave basin to optimise the positions of wavemakers and wave guides within the wave basin. The numerical model was also used to assess the development of the longshore current, which determined the placement of the model harbour within the basin (Grunnet *et al,* 2008, summarised in Gerritsen *et al*, 2009).
- Numerical modelling of the approach geometry for a dam model has been used at Utah State University to minimise the head box dimensions, while maintaining the correct approach flow. This reduced construction costs while increasing model size and reducing Reynolds

number scale effects. In a more traditional model a larger area would have been included in the physical model head box. Studies showed that most of this region could be modelled numerically as it has subcritical flow only.

Numerical models are commonly used as the first stage in modeling a system. They can then be used to design a physical model which occupies a part of the wider system only and which concentrates on the nonlinear phenomena of interest.

3.3 Physical model representation of one element of a system

The more straightforward (less nonlinear) aspects of a hydraulic system may be modeled adequately using numerical models, yet there may be elements of particular complexity or unusual arrangement that cannot be modeled with confidence using a standard modeling approach. The composite modeling approach to such a problem involves the following stages:

i. Initial modeling of the system using one or more numerical models. This stage is used to optimize the layout as much as possible;
ii. Physical modeling of the most complex part of the system with appropriate measurements to characterize the results;
iii. Incorporation of the physical model results into the next round of numerical modeling either by parameterization of them or through their use in calibrating the numerical model.

One example of this involves the design of lock filling and emptying (F/E) systems. A numerical model with 1D pressure flow and 1D open channel flow was used to model the F/E system. The head loss of each component must be represented in such a system, but this is difficult to estimate for a complex culvert. Therefore the numerical model was used to model the system with standard textbook head losses. A physical model of a culvert was constructed and run. Pressure gradients were measured and flow patterns were observed (as an even flow distribution is desired). The culvert design was optimized based on the physical model results. The head losses derived from measurements on the physical model were then incorporated into the numerical model so that the overall design could be optimized (Bousmar, 2010, personal communication).

Another example using lock filling (Bousmar et al, 2010) involved the design of the approach to a lock system on a river. This involved

i. investigating the backwater effect of the new structure on the river flood flow using a 1D numerical model,
ii. investigating the velocity field using a 2D numerical model and a physical model and
iii. analysis of the flow pattern, in terms of fluidity and safety of navigation (using a navigation simulator).

The physical model was found more adequate than the 2D numerical model in turbulent conditions, although it was more difficult and time consuming to extract velocity measurements.

Both of these examples are similar to the composite modeling approach advocated by Oumeraci (1999) for whom the principle of Composite Modelling consists in subdividing a very complex and complicated problem into several simple and more easily tractable processes which can be described by the most appropriate methods in order to get the most reliable process models, including physical and validated numerical and analytical models. These models should then be combined using a hydro-informatics approach. As the hydro-informatics approach taken commonly consists of the development of a numerical model including behavioral (parameterized) elements, this can be seen as a typical means of numerical model development. However, in these cases the physical model tests were designed to produce sit-specific and conditions-specific results, which were not intended to be generalized for use in a numerical model of other similar cases.

Kamphuis (2000, 2010) regarded composite models as a combination of complementing physical and numerical process models, each applied for a specific process or part (for which they are well validated) and linked by a computational module. Again, quantified interfacing between models and specifications of boundary conditions are crucial parts. Kamphuis states that the computational module that links physical and numerical elements could be as simple as a spreadsheet – in other words processed results from the physical model study can be used to influence the subsequent numerical modeling (as in the case studies above).

3.4 Modelling the model

One of the most significant benefits of composite modeling is "modeling the model", which means that the exact geometry of the initial or baseline physical model is numerically modeled at a 1:1 scale so that numerical modeling errors can be evaluated and corrected if possible. This quality control effort is effective in reducing or eliminating the uncertainties of the numerical model.

Once the numeric model has been calibrated or adjusted to the results of the physical model, it can be used to evaluate a myriad of discharges, velocities, water surface profiles and detailed surface pressures and shear stresses that are labour-intensive and expensive to perform in the physical model. Adjustments to the numerical model to match the physical model are normally done by adjusting surface roughness, turbulence model parameters and grid cell resolution until the correlation between the two modelling types seems reasonable.

An unusual extension of this composite modeling approach involved the physical and numerical models covering the same domains (van den Boogaard *et al,* 2009, summarized in Gerritsen *et al*, 2009, Gerritsen and Sutherland, 2011). Here wave propagation over a nearshore bar was modeled using a physical and a numerical model to determine the worst cases wave conditions at the toe of a seawall. The worst case was determined by the geometry of the nearshore bar and intertidal terrace, so several geometries had to be modeled for each wave condition. In general terms, physical wave experiments for near-shore problems are accurate but expensive and time consuming, while numerical wave modelling for these problems is flexible, relatively fast and cheap, but still much less accurate. An error correction technique was devised to use the results of the physical model to correct the results of the numerical model. The error correction procedure was based on an artificial neural network model of type Multilayer Perceptron. *A priori* knowledge and analysis were used to reduce the dimensionality of the problem to acceptable limits. In this way the speed and flexibility of the numerical model was combined with the accuracy of the physical model so that the worst case of nearshore bathymetry could be determined. Moreover, the above combination of both models significantly reduced the number of flume experiments needed to derive the most critical bed geometry for the defined problem.

The calibrated or corrected numerical model is then available to undertake additional model runs that would be too time consuming in a physical model or were only considered after the physical model has been decommissioned.

4 Summary

This paper has shown that many problems can be addressed better by the combined use of physical and numerical models, compared to the use of one model alone. Composite modeling provides a unique opportunity for researchers and engineers to understand the uncertainties and limitations of both the physical model and the numerical model, since their parallel operation allows for direct comparison and calibration. When complex three-dimensional flow conditions are being modeled, numerical models are often limited in their ability to simulate the flow field in all regions as compared to the physical model. Composite modeling allows for the verification and validation of flow rates, water surface profiles and point velocities within the flow domain and consequently determines specific regions within the numerical model that are not being simulated accurately.

There is a range of ways in which physical and numerical models can be combined, including:

- Traditional nesting where a physical model is a detailed representation of a system, which is modeled at a larger scale (and at a more general level) in a numerical model;
- Numerical modeling can assist in the design of physical models by helping to set the location and type of boundary conditions that are to be applied;
- Numerical pre-modeling also provides information about potential problems associated with the theoretical design or proposed design changes to the structure, thereby reducing the number of physical modeling configurations necessary during the physical modeling portion of the study. This pre-modeling effort saves time and money once the physical modeling has commenced.
- Modelling the model can allow a numerical model to be calibrated or corrected using the physical model results.
- The calibrated or corrected numerical model is then available to undertake additional model runs that would be too time consuming in a physical model or were only considered after the physical model has been decommissioned.

These techniques should be developed and disseminated. The quantification of the strengths and weaknesses of physical and numerical models should be encouraged, to replace the usual subjective standards. More and more complex problems are being modeled using physical and numerical models of increasing complexity. However, advantages can still be found in utilizing the complementary strengths of each.

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