Numerical Modeling Strategies in Coastal Hydraulic Studies

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1. Introduction

Development of the coastal zone in Malaysia has seen an upsurge in recent years with the proliferation of coastal resorts, marinas, and infrastructure such as power plants some of which are on reclaimed lands. While some major coastal developments such as the Kedah coastal reclamation (except for the Pulau Bunting reclamation) have been put on hold since the economic downturn, others have picked up the pace and are in various stages of implementation that range from feasibility study, environmental impact assessment, engineering design, to construction. While this seeming upswing may signal that the country is pulling out of the doldrums, the potential for the coastal environment to be continuously and increasingly stressed has also been correspondingly enhanced.

Hence, there is a greater need to ensure that the development is not detrimental to the environment. At the same time, these developments are gradually taking place at more exposed locations. There are also increasing threats from a changing coastal environment brought about by the propects of rising sea level. All these place demands on our engineering ingenuity to be able to better predict the characteristics of the elements, thereby leading to improved design to withstand these environmental forces.

Coastal hydraulic studies are often conducted both to assess coastal environmental impacts and to furnish appropriate environment loads and parameters for configuration and structural design [see Drainage and Irrigation Department (2001a), which lists a variety of coastal development activities where a coastal hydraulic study is required]. Of course coastal hydraulic studies are also conducted to elucidate the mechanisms of the various coastal processes and their mutual interactions in an effort to add to our corpus of knowledge of the coastal science and engineering, which in turn is put into use in coastal assessment and design. However, this paper will focus on the first two domains, they being the primary focus of practicing engineers.

The days of analytical approaches and simple spread-sheet type computation have given way to the use of numerical models that have grown in sophistication and complexity from one-dimension to three dimensions, from problems of pure hydraulics to environmental and even ecohydraulics where physical, chemical, and biological processes are simulated in an interactive manner. Hence, numerical modeling has become an indispensable tool in coastal hydraulic studies. From public domain numerical algorithms to commercial software packages, numerical models have become the mainstay of our repertoire of capability in trying to understand the behavior of observed phenomena (diagnostic mode) and, hence, predict their future trend (prognostic mode). Attendant to the availability of a plethora of numerical models is the wide range of choices that are open to a practicing engineer. To the extent that numerical models are but models of reality that employ simplifying assumptions, this paper explores some of these choices in order to distil a set of numerical modeling strategies that meet the requirements of the regulatory framework and the objectives of the coastal hydraulic studies consistent with the degree of modeling details required.

2. Numerical Models as They Are

At the outset, it is useful and indeed advantageous to come to some basic understanding of what numerical models entail. Simply put, they are a mathematical representation of the physical reality in the form of equations (the governing equations), which are then solved to forecast the outcome based on knowledge of the initial/boundary conditions and evolution of the forcing terms. In hydrodynamics, which is the primary driving forcing on a range of coastal phenomena such as sediment trasport, shoreline/profile evolution, and movement of various water quality constituents, the governing equations are the Navier-Stokes equations, whereas the forcing terms are atmospheric inputs (atmospheric pressure and the resulting wind field) and/or gravitational interaction of the sun-earth-moon system (tides). Initial conditions describe the sea status (current speeds and directions, water levels) in the entire computational domain at the beginning of the computation while the boundary conditions refer to the characteristics of the periphery that envelops the computational domain (bottom bathymetry, water level changes at model extremities).

Several sources of uncertainty or error that produce inaccuracies can be identified from the above formulation:

a) Model simplification such as depth averaging leading to incomplete formulation;
b) Domain discretiztion, hence, the model is unable to resolve subgrid phenomena and is fraught with numerical diffusion/dispersion;
c) Model parameterization as some parameters cannot be directly measured (bottom friction, eddy viscosity); and
d) Specification of initial/boundary conditions that cannot be precisely defined leading to the use of crude data.

Hence, numerical models can yield incorrect results at worst and qualitative results at best. However, armed with an understanding of relevant coastal processes, the behavior of the governing equations, the physically meaningful bounds of parameter/coefficient values, and the working of the numerical solution methods (instability, truncation error, smoothing, numerical diffusion/dispersion), it is possible to interpret the qualitative results into quantitative terms, which can then be used to define problems, aid in understanding, point to possible solutions, give approximate answers, and test sensitivity to variations in parameters (Kamphuis, 2000). In addition, the forte of numerical models really lies in their ability to simulate large areas over large time spans.

3. Model Selection

The approach to conducting a coastal hydraulic study involves primarily the use of numerical models to simulate physical processes by representing them using mathematical equations, which are then solved using numerical algorithms. Hence, the reliability of the simulated results hinges to a large extent on the choice of the model capable of representing the primary processes, with the implicit understanding that secondary processes are omitted as the aim is to model the essentials. Toward this end, a conscious choice can be made to use an existing model or to develop from scratch. For complex models, formulating algorithms, devising data management schemes, writing and debugging code, and testing new programs are extremely time consuming and expensive. Time is usually at an extreme premium and undue concentration on developing the numerical model can distract from focusing on the actual environmental concern. Often the use of existing commercial software packages is the only feasible way to conduct a hydraulic study, given the constraints on funds and time.

In general, the role of numerical models is two-fold: firstly to contribute to a better understanding of real-world processes, and secondly, to provide quantitative information to support decision-making activities by strengthening the knowledge base. In this respect, application of numerical models depends on:

a) the real-world processes being modelled vis-a-vis the capabilities and limitations of the mathematical equations that represent the essence of these processes;
b) computational techniques for solving the equations;
c) data availability and limitations;
d) development of model parameters;
e) model calibration and verification techniques.

Two chief considerations in selecting the numerical models are whethere they are generalised and operational. A generalised model is one that is applicable to a range of problem settings entailing systems of varying configurations and at different locations as opposed to one that is designed for a specific application at a specific location. On the other hand, a well-tested and adequately documented model such that it can be used reliably by professional practitioners other than the model developers is considered to be operational. Such a model is user-friendly and backed by proper documentation and user support. For example, with a wide user base world-wide and in Malaysia as well, the MIKE 21 suite of commercial software package developed by Danish Hydraulic Institute (DHI) qualifies on both counts. The periodic issuance of updates and the successful series of DHI Software User Conferences, which focuse on sharing of experiences and lessons learned among experienced and new users as well as dissemination of new findings of research and development efforts, further testify to the wide acceptance of DHI software in hydraulic studies. Lest the above be misconstrued as a sales pitch for MIKE 21, there are also other numerical models that have been used in Malaysia a fair selection of which is mentioned in the Checklist for Development Applications (Drainage & Irrigation Department, 2001c) such as TELEMAC, UNIBEST, and DIVAST. However, other classes of numerical models, while less frequently used in Malaysia, are worthy of consideration too as discussed next.

4. Coastal Models

In a typical coastal setting, the inputs are the currents and the waves, which are themselves outputs of the hydrodynamic modeling. The operating processes are those governing sediment transport, pollutant dispersion, and nutrient cycling. The outputs that are of engineering and societal concern are morphological change, environmental impact, and water quality alteration. As alluded to in the previous section, numerous numerical models are available and here they are conveniently grouped into the following categories for discussion purposes:

a) Advanced Commercial Software Packages Marketed by Internationally Renowned Hydraulic Engineering Consultants
MIKE 21 and TELEMAC are typical examples under this category. These are continuously been updated through in-house research and have excellent technical support and a wide base of users who meet regularly. But they are also expensive and priced beyond the reach of most consultants.

b) Public-Domain Numerical Codes-Turned-Commercial Software by software houses/university subsidiary companies
These are numerical codes originally developed through government-funded university research that are linked by purpose-designed pre- and post-processors (the user interface) by a third party and repackaged as proprietary software. However, the constituent modules remain in the public domain and their source codes are available for adaptation. Compared to (a), the technical support may seem ad hoc, but the price is also correspondingly affordable. Examples are Surface-water Modeling System (SMS), Coastal Engineering Design and Analysis System (CEDAS).

(c) Public-Domain Numerical Models
These are the various freeware available for download from the Internet such as HEC-RAS and SBEACH. Technical support is almost non-existent and they are used at the users' own risk. They also tend to be for more simplified conditions and are popular choices as teaching aids to demonstrate basic principles.

(d) Computational Fluid Dynamics (CFD) Codes
Computational fluid dynamics (CFD) has been characterized as a "powerful and very effective supplement to traditional laboratory studies and has already revolutionized and forever changed such areas as aerodynamics, turbomachinery, and marine hydrodynamics" (Sotiropoulos & Wei, 2001). Fueled by the advent of high power supercomputers in the late 1970s and early 1980s, CFD capabilities now manifest in the form of numerous academic and commercial software packages applied to solving fluid flow problems in an industrial setting such as aerospace, automotive, chemical and mechanical engineering. Comparatively, similar application in the field of civil and environmental engineering has only taken off in recent years, notably in the design and operation of hydraulic structures and the assessment of project impacts on water quality and the aquatic environment. With increasing use and ever-shrinking cost of computing in accordance to the Moorse's Law, there is even an euphoric expectations of these

"virtual hydraulic models" becoming the tool of choice in the near future and relegating the conventional physical scale models into the obsolete realm of the slide rules.

While CFD numerical simulations provide the full hydrodynamic description of the flow field, they are expensive with respect to both time of execution and cost, not to mention the details of experimental and field data needed for validation. Therefore they are often used to examine very specific problems such as those occurring in the vicinity of natural obstacles or man-made hydraulic structures in the water way (Muste et al., 2001).

(e) Manuals/Nomographs

While these are not numerical codes in the normal sense of the word, they are often generated by numerical models for a range of expected field conditions and the results portrayed in the form of nomographs. A classic example is the Shore Protection Manual (CERC, 1984) who has been the companion for coastal engineers on a world-wide basis. They still serve a purpose for rapid evaluation at the preliminary scoping/assessment stage a good example of which is the use of the diffraction diagrams. The SPM has been replaced by the interactive Coastal Engineering Manual (CEM) that costs quite a sum. However, the static documents are still available from the Coastal and Hydraulics Laboratory web site (http://chl.wes.army.mil)

The choice of which category of models to employ depends to a large extent on the job at hand (the site characteristics whether exposed, regular, extent of prior studies), the objective (whether preliminary assessment, EIA, engineering design), the technical level of the consultant (whether generalist, specialist, experienced/novice modeler) and the time and fund limitations while satisfying the regulatory requirements.

As a fitting end to the above discussion, it is perhaps instructive to cite the philosophy of the program called Coastal and River Engineering Support System (CRESS), which is a collection of small routines, each containing a formula, or groups of formulae, important in coastal and river engineering where the input and output are highly standardized, developed by IHE, Delft (http://www.ihe.nl/he/topics/dicea/cress.html):

> "In mathematical modelling of coastal processes there is in general a tendency to make programs more sophisticated and more advanced. The consequence of this modelling is that models become usually more specialized, and also more difficult to handle.
>
> Although much effort is paid to the user friendliness of systems, general systems require much input, which has to be defined in some way. Most programs nowadays can be handled relatively easily only if one is familiar with the program.
>
> On the other hand, 90 % of the problems in engineering are rather standard problems. These problems require only the application of very few formulae. Continuous research is going on to improve the quality of such formulae,

> although also here is a tendency to concentrate on the more exotic cases. This is very understandable, because for a researcher the challenge of such problems is much more attractive. For the design engineer, this development is not so attractive, because for his daily work he is therefore often condemned to use outdated reference material. Especially engineers working in smaller companies or agencies have difficulties is accessing the latest developments. The Shore Protection Manual is still their major source of reference information.
>
> Because application of a dedicated program requires familiarity with the input structure, many designers having a minor problem, will not use such dedicated programs. The time they have to invest in learning how to handle the program is too much in comparison with the importance of the problem. So in such cases designers often go back to graphs and design manuals."

It remains to be seen how the hydraulic engineering community in general will react to this plea, given the increasing complexity of the hydraulic engineering problems that it has to handle, a legacy of the increasing pressure we put on the coastal zone.

5. Model Validation

Good modeling practice requires a comprehensive understanding of many related and complex physical/chemical/biological processes. And this understanding often comes with experience in using the models, which distinguishes an experienced modeler from a novice modeler. According to Whittemore (2001), a novice modeler has far too much confidence in his simulations, fails to recognize inherent limitations, and is quick to believe that his model is a true mathmatical representation of reality. While model formulation, with its focus on the numerics that has rigorous mathematical treatment as its hallmark, can be considered as a science, model validation itself is more art than science wherein the experience of the modeler is paramount.

A rather objective way to evaluate the integrity of a numerical model, which in fact is a necessary condition for model acceptance, is model validation. Frequently this is the only indication that the simulation is close to observation.

Model validation comprises three essential steps (Kamphuis, 2000):

a) benchmarking through reproducing analytical solutions;
b) calibration through reproducing measured field data; and
c) verification through reproducing additional field data and post-construction data with the calibrated model.

For example, in developing a 3D numerical model of sediment transport processes, a necessary first step is to apply the model to simulate situations for which an analytical solution (e.g., spherical annular basin and circular island for hydrodynamics and equilibrium profile and net entrainment at the bed) and laboratory measurements exist (Singh and Ghosh, 2000). Other benchmarking tests include simulating analytical solutions for simple boundary conditions (e.g., 1D shoreline model vs diffusion solution) and against standard laboratory measurements. Field data are used to correct model results on the premise that output parameters derived directly from field measurements contain less uncertainty than model results. In this respect, model results are viewed as an extension of existing field conditions. Often times the above procedure is short-circuited into comparison, or in the words of Kamphuis (2000), "subjective turning of knobs to produce "reasonable" pictures". In that case, model calibration often becomes nothing more than curve fitting exercises in which parameter values are varied until a match between simulated and observed parameters is achieved, often displayed graphically in terms of time series plots or scattered plots. This match becomes the sole end point in calibration.

Therefore, quantitative estimates of the "goodness-of-fit" are necessary to lend credence to the model performance. These can be in the form of error bands or tolerances of the deviation of simulated results from measurements. For example, Kraus and Militello (1999) reported on a study on a multiple inlet system using a 3D numerical model that the root-mean-square (rms) difference between calculated and measured water levels at three locations were 5.2, 4.8, and 4.2 cm while the rms error between calculation and measurements for current speed at two of these locations were 4.9 and 1.4 cm/s. They also mentioned that the bottom friction coefficient was the only parameter adjusted for the calibration, which took typical values, based on the bottom and side bank conditions. In their case, the Manning coefficient ranged between 0.022 to 0.028 $s/m^{1/3}$ (oyster bed); but calibration required larger values up to 0.1 $s/m^{1/3}$ in the vicinity of the mouth of the navigation channel, to account for transition losses at the entrance. These are parameter values within the physically meaningful bounds.

In another study of an estuary, Chau and Jiang (2001) reported rms errors for the computed tidal level, flow direction, and velocity (depth-averaged) based on 1-month comparisons as 0.14 m, 17°, and 0.07 m/s, respectively, and thus concluded that the computed flow direction and velocity coincided well with the observed data.

In the same vein, model validation for coastal hydraulic studies should demonstrate agreement with pre-set criteria established for a specific parameter to vary, In this respect, Department of Irrigation and Drainage (2001b) has done an admirable job in publishing general calibration "tolerances" and developing an appropriate roadmap to effective model calibration.

A potent adjunct to numerical models is the powerful visualization (including animation) used to present modeling results. While this has definite demontration/illustration value as far as client relation is concerned, it must be realized that they are only as good as the data that go in. The client must be made aware of the basic approximations built into the various modeling strategies so that they can understand the range of applicability and limitation.

6. Future Trends

Fortunately there is no dearth of glimpses into the future of coastal hydraulic studies in general and numerical modeling in particular made in the open literature and this has helped to crystallize some of the future development reported herein.

The future is in integrating physical and numerical models and field data. This combined use will offset the demerits of each while complementing each other to present itself as a viable tool of investigation and assessment. For example, very large physical models entailing small prototype sections, computer controlled boundary conditions with scales of n = 1 to 5 are already possible in oscillating tunnels and wave flumes (Kamphuis, 1999). Kamphuis (1999) also hastened to add good common sense to the above mix

The resulting paradigm termed composite modeling is also described as comprising physical model as the bricks (generic and repeatable) and the numerical model as mortar (what if analyses), both validated by field measurements (Kamphuis, 1999).

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8. References

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