Jurnal Kej. Awam Jil. 9 Bil. 2 1996

COASTAL HYDRAULICS MODELING: MODEL SET UP AND DATA COLLECTION

by

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ABSTRACT

The interaction of hydrodynamic forces in the coastal and estuarial areas is a complex phenomenon. It may however, be simulated using computer models. The use of numerical models helped in analysing and investigating hydrodynamic behaviour. This in turn facilitated the processes of design and decision making in coastal engineering design works. There are various types of computer model in use but for each application it is important to apply the correct model set-up to ensure optimum execution and reliable outputs. This paper introduces typical sample of such models with greater emphasis on tidal models. The practical aspects of setting up the model and data collection are presented. This is based on many years' experience of using and developing such models.

INTRODUCTION

Malaysia is experiencing a land reclamation mania. The recent announcement of the government's approval for a new international airport has taken everyone by surprise. The reason is not so much because of it being the third international airport serving the northern peninsular Malaysia region but for its proposed location on reclaimed land in the Straits of Melaka, emulating Kansai International Airport in Japan. This follows recent proposals for major reclamation along the coastline of Perlis and Kedah, reputed to be the biggest single coastal land reclamation project in the world. Currently under construction is a man-made island off the coast of Bandar Hilir Melaka.

These land reclamation activities require a large amount of fill material, of which marine sand is the most suitable and economical choice. Removing large chunks of the seabed to satisfy these demands is, by itself, considered a major coastal engineering endeavor. Other interesting coastal engineering related projects being considered are the second bridge for Penang Island and the bridge linking Peninsular Malaysia to Sumatera.

All these mammoth developments must be properly monitored, coordinated and supervised by the relevant authorities so that any undesirable side effects of this race for modernization and development can be curtailed. Such undertaking is being implemented by requiring the submission and adherence to any recommended measures of the Environmental Impact Assessments (EIA). EIAs are required for any development projects that might affect the status quo of the existing in situ environment. A major component of EIAs for land reclamation or coastal development projects is the hydraulic study.

A hydraulic study consists of evaluating the existing hydraulic environment of the project area, assessing the envisaged changes to the present environment due to the implementation of the project and to recommend any mitigating measures for implementation by the project proponents. Mitigating measures are meant to eliminate or minimize adverse environmental impacts of the project. Compliance is strictly for the developer to follow with enforcement by the relevant government agencies.

As such, it is very important for the hydraulic consultants to arrive at a reliable and realistic impact evaluation so that the interest of all parties is safeguarded. A grossly misjudged interpretation may unnecessarily elevate the cost of the project, or worse, it could cost irreplaceable damage to the ecosystem. Thus, the need for sound engineering judgements, aided by predictive tools such as numerical or physical modeling is vital. Numerical modeling is at the forefront of this task. It is indispensable, so much so that the Department of Environment requires computer modeling for all EIAs submitted for approval.

One possible pitfall of relying on computer models is the total dependence on the numerical result with little consideration for engineering judgements. We are usually impressed by colorful graphics and presentations that accompany the outputs of computer model that we may forget basic logical thinking. This is particularly important to model users where they should use the model with caution, follow all the ground rules regarding the setting up of the model and to always remember that even the most sophisticated of programs on the fastest supercomputers have their limitations when simulating the hydrodynamic forces. It is the objective of this paper to address this issue and to give some guidelines for modeling.

THE HYDRODYNAMIC MODEL

A hydrodynamic model refers to either a numerical or physical representation of the real hydrodynamic system. Tests conducted on these models may be interpreted to relate to the prototype and based on these tests, the performance of various designs and configurations can be evaluated. In hydraulics, physical modeling play a significant role in design assessments and hydrodynamic behavior studies but they require laboratory space and skilled artisan for construction, are relatively expensive and time consuming to test and build and, in most cases, unrecycleable.

On the other hand numerical models are more flexible in that they may be used anywhere provided the right software and hardware are available. Various designs and configurations may be tested for the optimum outputs. It is only limited by the computer storage capacity. Numerical models are programs written to mathematically represent the actual physical processes occurring at the coastal region. Due to the complexity and randomness of the coastal environment, there will be some degree of simplicity of the actual processes and assumptions in the structure of the mathematical solution. From hereon in this paper, the hydrodynamic model refers to the numerical type.

Hydrodynamic forces acting on the coastlines include wave, wind, current, tides and river discharges. These forces act independently or in combination with each other in variable degrees of magnitude, direction and frequency. Apart from these, other important parameters are the coastal bathymetry, bed material composition, water and sediment profiles and the shoreline configuration. All the forces stated above are unique for each general location. For example, you cannot reliably use the Penang tidal condition for Kedah without first conducting a field survey to confirm it.

As mentioned earlier, numerical model is just a tool to help in engineering judgement. Developing such models requires good mathematical and computational background but implementation demands engineering skill, judgement and experience. The output obtained is subject to the quality of data available for calibration and setting up and the manner these data are used in each particular case. Understanding the physics of fluid flow and realizing the limitations of the governing equations and numerical techniques is a good start towards this.

Types of Numerical Model

There are many types of numerical model developed by researchers from all around the world. Each has its own advantages and specialty and some are specific for certain type of problems. A single common model which integrate all possible hydrodynamic conditions is possible but it would be very expensive to set up and calibrate to reach the required level of confidence for result accuracy and reliability. Some complex models need high specification machines to run comfortably.

The most common type is the 2-D depth averaged tidal model. The vertical-variation of the tidal current over a particular point in the model area is averaged. It assumes that the tidal current is represented by a single mean value. This assumption is reasonably acceptable for shallow regions provided that the model domain is not subjected to stratified flows, such as those observed in estuaries, or where the vertical velocity component is substantial enough such as near very steep bed slopes. One might argue the reliability of such an assumption because in the real situation this is not the case but for most applications, the results are sufficiently accurate.

In highly turbulent areas with significant velocity variation over depth, a more detailed model such as 3-D models may be more appropriate. The 2-D depth averaged models give the most value-for-money after considering the computer time and the quality of results obtained. 1-D models are also available but their applicability is mainly confined to predominantly uni-directional flows such as in rivers or channels or as a preliminary assessment tool prior to a more detailed modeling work. This type of model is also useful in analyzing the beach profile evolution over particular cross-sections of a beach where a quick and indicative result is desired. They are also the cheapest to run on the computer.

The next breed of tidal model is the 3-D type. This is the most expensive to develop and run and normally requires high-end computing power. Models of this type are useful in studying flow profiles at various depths of the study area. Where stratification prevails or where the vertical component of flow is significant, this type of model is the most appropriate. However, one must bear in mind the costs incurred in terms of run-time, model setting-up and calibration. A 3-D model would require a more intensive data observation and monitoring for calibration and validation when compared to a 2-D model.

The standard of hardware normally required to run the above models is at least a 286 PC for the 1-D model. However, as they were continually being developed to include various improvements to the solution techniques and calculations, the minimum hardware requirement tends to increase. Nowadays, a Pentium based PC is the basic entry system to run a 2-D model comfortably. Nevertheless, there are some models which were primarily developed with complex and sophisticated features giving impressive outputs and versatile pre- and post-processing capabilities even though they only work in 2-D. A Workstation is a must for these type of programs. This will require a higher initial investment for the user in acquiring the hardware. Nevertheless, with the coming development of faster PC chips which is said to be approaching the Workstation processing power, the use of PCs for such models may still be a cheaper and viable alternative. The most recent development is to adapt existing software for the Supercomputer or to customise the algorithm for parallel processing.

Figure 1 illustrates the processes involved in applying the modelling tool in a typical coastal engineering project. It includes both types of model, which can either be applied individually or in tandem. Within the numerical model framework, the steps involved are data and boundary condition input, which constitute the model set up, execution, calibration and result output and analysis.

Using established and well-proven software, coupled with the proper technical skills, and a realisation of the limitations of the models, numerical models are essential tools for the engineers or planners. A realistic picture of the future scenario can be predicted with good accuracy.

There are many softwares now commercially available. At the forefront are those marketed and developed by well-established hydraulic research institutions from Denmark, United Kingdom, USA, France and the Netherlands. Locally, local researchers have successfully developed similar software but they need to be further improved for commercialization.

Governing Equation

Numerical modeling involves solving a set of equation that governs the flow hydrodynamics. Normally, for tidal models, the independent variables are water depth and velocities in 1-, 2- or 3-D format. The solution to this gives the flow hydrodynamics which enables us to visualise the time-varying parameters within the model boundaries. In addition to the flow, it is also normal to extend the computation to include bed and suspended sediment transport, bed evolution, thermal distribution or pollutant dispersion. Wave models can predict wave refraction, diffraction and reflection.

Several numerical techniques have been applied to solve these governing equations. Among them are the finite element method (FEM), finite difference method (FDM), finite volume method, boundary element method and the inverse method. Each method has its advantages and while it is not the main purpose to discuss the their merits and setbacks, it is sufficient to mention that most commercial hydrodynamic software use either FDM or FEM.

Tidal models are the most common coastal hydrodynamic simulators. This is due to the strong influence of the tidal forces near the coastal areas. Wave induced current modelling are sometimes included when the effects of waves are significant. Upon reaching the flow hydrodynamic solution, it is normal to use these results as the driving force for other phenomena of interest such as pollutant and thermal dispersion, sediment transport, bed evolution and oil spill tracking. **Figures 2, 3, 4, 5, 6** and **7** show typical results and output from such models.

A tidal hydrodynamic model solves for the Shallow Water Equation derived from the Navier-Stokes equations for incompressible liquids. For a two-dimensional application, a depth-averaged flow is assumed due to the high degree of vertical uniformity of the horizontal components of velocity. To save on computational storage, the Shallow Water equations (1) may be solved by a two-stage computation at half and full time-steps. The resulting consistent mass matrix, M in equation (2) is lumped and solved by using an iterative solver.

$$\frac{\partial U}{\partial t} + \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} = R \qquad (1)$$

Where $R = R_s + \dfrac{\partial R_{dx}}{\partial x} + \dfrac{\partial R_{dy}}{\partial y}$

The independent variables, $U = \begin{bmatrix} h \\ hU_1 \\ hU_2 \end{bmatrix}$

Convective fluxes, $F_x = \begin{bmatrix} hU_1 \\ \beta hU_1^2 + \frac{1}{2} gh^2 \\ \beta hU_1 U_2 \end{bmatrix}$, $F_y = \begin{bmatrix} hU_2 \\ \beta hU_1 U_2 \\ \beta hU_2^2 + \frac{1}{2} gh^2 \end{bmatrix}$

Diffusion terms,

$$R_{dx} = \begin{bmatrix} 0 \\ 2\frac{\mu_H}{\rho}\frac{\partial U_1}{\partial x} \\ \frac{\mu_H}{\rho}\left(\frac{\partial U_1}{\partial y} + \frac{\partial U_2}{\partial x}\right) \end{bmatrix}, R_{dy} = \begin{bmatrix} 0 \\ \frac{\mu_H}{\rho}\left(\frac{\partial U_1}{\partial y} + \frac{\partial U_2}{\partial x}\right) \\ 2\frac{\mu_H}{\rho}\frac{\partial U_2}{\partial y} \end{bmatrix}$$

Source terms, $R_s = \begin{bmatrix} 0 \\ -gh\frac{\partial z_b}{\partial x} + \frac{\rho_a}{\rho} C_d |W| W_1 - \frac{g|U|U_1}{C_c^2} + hf_1 \\ -gh\frac{\partial z_b}{\partial x} + \frac{\rho_a}{\rho} C_d |W| W_2 - \frac{g|U|U_2}{C_c^2} + hf_2 \end{bmatrix}$

$$M\Delta U = f^n \qquad (2)$$

Where: h = depth of water; U_1, U_2 = depth averaged velocities in x- and y-directions respectively; g = acceleration due to gravity; ρ, ρ_a = water and air density respectively; β, C_c, C_d = momentum, Chezy's and drag coefficients respectively; f_1, f_2 = coriolis forces; μ_H = horizontal eddy viscosity; W_1, W_2 = mean wind speed in the two horizontal directions; ΔU = unknown terms; f^n = known terms.

Sedimentation can be calculated using equation (3)

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(\varepsilon_1 \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_2 \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(\varepsilon_3 \frac{\partial C}{\partial z}\right) +$$
$$\frac{\partial}{\partial z}(\omega C) - U_1 \frac{\partial C}{\partial x} - U_2 \frac{\partial C}{\partial y} - U_3 \frac{\partial C}{\partial z} \qquad (3)$$

Where : C = sediment concentration; U_1, U_2, U_3 = depth-averaged velocity in x-, y- and z-directions respectively; ε_1, ε_2, ε_3 = component of diffusion coefficients and ω = sediment fall velocity.

Bed evolution equation is in the form (4)

$$\rho_B \frac{\partial z_B}{\partial t} = D - P \tag{4}$$

Where: ρ_B = bed density; z_B = bed level; D = quantity of deposition and P = quantity of material picked up from the bed by the flow.

Heat transport equation can be written as (5)

$$\frac{\partial (hT_t)}{\partial t} + \frac{\partial (hU_1 T_t)}{\partial x} + \frac{\partial (hU_2 T_t)}{\partial y} = \frac{A(T_e - T_t)}{\rho C_p} + \frac{\partial \left(hK \frac{\partial T_t}{\partial x} \right)}{\partial x} + \frac{\partial \left(hK \frac{\partial T_t}{\partial y} \right)}{\partial y} \tag{5}$$

Where: U_1, U_2 = depth-averaged velocity in x- and y-directions respectively; T_t = temperature; K = diffusivity constant; $A/(\rho C_p)$ = temperature exchanges with the ambient and T_e = ambient temperature.

Pollutant transport governing equation is as (6)

$$\frac{\partial C_t}{\partial t} + \frac{\partial (U_1 C_t)}{\partial x} + \frac{\partial (U_2 C_t)}{\partial y} + \frac{\partial (U_3 C_t)}{\partial z} = \frac{\partial}{\partial x}\left[R_{d1} \frac{\partial C_t}{\partial x} \right] + \frac{\partial}{\partial y}\left[R_{d2} \frac{\partial C_t}{\partial y} \right] + \frac{\partial}{\partial z}\left[R_{d3} \frac{\partial C_t}{\partial z} \right] - \gamma C_t \tag{6}$$

Where: C_t = depth average pollutant concentration; R_{d1}, Rd2, R_{d3} = dispersion coefficient; γ = decay coefficient and U_1, U_2, U_3 = depth-averaged velocity in x-,y- and z-directions respectively.

MODEL SET-UP

Extreme care must be exercised when setting up a numerical model for practical applications. This is to avoid misinterpretation of the result of the computations. Model setting up includes defining the limits of the modeled area, locating the position of boundary condition prescriptions and determining the time frame for the simulation.

It is important to understand the actual mechanics of the phenomena involved and to identify and define the problem. Among questions that need to be addressed include:

- Is the model domain bordered by the coastline or situated out in the open sea?
- Does it involve changes to the existing bathymetry or shoreline? E.g. land reclamation, dredging or sand mining.
- Is it for preliminary investigation or detailed design simulation?
- Will the model output be used for design? If so, are several alternatives being considered?
- Are we testing for the worst case scenario or is it under normal prevailing conditions?
- What are the dominant hydrodynamic forces? Will there be wave/current/river interaction?
- Is the model able to simulate the dominant hydrodynamic forces? If not, what are the limitations?
- Is 3-D modeling needed?
- Where in the model domain are the critical areas? E.g. high stresses, backwater or strong velocities.
- What are the critical forces to be evaluated? Sedimentation, scouring, erosion, wave reflection etc.

One other consideration is in the objective of the modeling task itself. Are we evaluating a single fixed condition or are we in the process of determining the best layout. The latter will require extensive evaluation of the hydrodynamic scenario of several alternatives and will need numerous repeat runs. Hence the user should set-up the model in such a way as to facilitate reruns. After identifying and defining the problem, the next step is to set-up the model itself. The processes involved are described in the following sections.

Model Domain

Establishing the location of the model domain boundary with respect to the study area needs careful consideration. This is because we are trying to simulate the flow in a continuous body of water by representing it with an area of finite size i.e. we calculate for unknowns within this domain based on the given initial and boundary conditions.

Physically, the model boundary line does not exist. Therefore, if there are reflections created by steep bed slopes, constrictions or obstructions lying just outside the model boundary, in reality, they will be transmitted back into the model area. Such signals were not included in the numerical calculations because their source is outside the domain. This could lead to misleading results in the model. Hence, to avoid this, it is important that the open boundary is not placed near these features. If such features need to be included, they must be placed within the model domain. It is normal for the model domain to extend up to 40-50km away from the area to be studied. The presence of mathematical boundaries may erroneously influence the result. It is important to allow flow to be well established around the location of the study area.

Grid Sizes

A model domain is first discretized into a finite number of grids or elements. The computation will work out the result at the nodes or grid points. The greater the number of nodes is, the longer will be the computational time. If there are too little nodes, the flow field will have coarse resolution and this may even lead to error in interpretation. In order to optimise the domain discretisation, it is advantageous to have variable grid sizes over the model domain. Fine grids should be applied at critical areas and they should be made progressively coarser as we move away. For a typical finite element model, it is usual to have element sizes ranging from 5m to 500m in a single triangulation.

When a variable grid size is not possible, nesting or patching technique can be used. This involves constructing and executing several layouts of the domain with the coarsest grids covering the biggest area and the finest grid placed over the smallest area i.e. the area of interest. This enables the simulation to be made over a very big area using a coarse grid, thus eliminating or reducing any boundary effects. At the same time the necessary accuracy and resolutions can be applied only at areas where they are required. This strategy helps to reduce computational costs. The result of the coarse grid computation is used to feed the boundary condition of the finer grid domain. Over several steps of refining, the desired result can be achieved. The size of the element is also important in defining the outline of the coastline, structures or islands within the domain. Wave agitation model will normally require fine grid all round and thus the size of the model domain is quite limited.

Boundary Condition

For a model to have a unique solution, we need to specify the appropriate boundary conditions around the model boundary. These are usually the water levels or velocities at open sea boundaries, discharges at river, outfall or intake boundaries and a zero normal velocity along the land boundary. At the open sea boundary, the simplest is to implement water level boundary conditions. This is because linear interpolation of the water levels along the boundary can be carried out from established and temporary tidal stations.

The location of any data sampling points must be such that it facilitate defining the boundary condition and also for calibrating the model. Data collection is a very expensive exercise. Thus coordination and planning is the keyword to be followed in any modeling work. The modeler should first evaluate all existing data before collecting new data. He should also plan for the layout of the model boundary so that sampling points can be correctly placed. Cases of redundant data or insufficient data are not uncommon. Sometimes, a repeat data collection exercise needs to be carried out due to improper planning.

DATA COLLECTION

The process of data collection is inevitable for any modeling to be calibrated. Most hydrodynamic data are time-dependent and site specific. Some vary annually, like the monsoon season and annual tidal variation, while some vary every second of the day, like the daily tidal level variation. The type of parameters recorded depends on the type of modeling but they are usually the bed bathymetry, tide level, water current, wave height and period, bed material sampling and water sampling.

The extent of the bathymetric survey undertaken must cover at least the immediate project area. Preferably, it should extend well beyond it. If this is not possible, the next best thing is to superimpose the information gathered from existing charts over the blank areas. The levels recorded must be reduced to a common datum. The Land Survey Datum (LSD) is a typical datum that is normally used. The tide level readings must also be reduced to the same datum when they are used in the calculations.

In most models, all the relevant reference levels (LSD, MSL, HAT, LAT etc) are usually converted to a common one but this must be double-checked by the user. Hence, data may be stored with respect to their original datum but we must ensure the appropriate conversion is made beforehand. Bathymetry data must be digitized and stored. The bed level at each node is interpolated from the digitized data.

When rivers are present, a discharge or velocity boundary condition should be implemented. This may include suspended sediment discharge for sediment dispersion studies. To record this parameter, it is usual to sample over a few points along the river. By consolidating this with cross-section leveling, the discharge of the river can be calculated. Suspended sediment concentration can be determined by collecting water samples at a river cross-section over a 24 hr period at intervals of about 2 to 3 hours. Establishing indicative coastal sediment deposition involves setting up several sediment traps along the coastline and monitoring the sediment buildup over several months, preferably 1 year.

Tide level observations must be conducted continuously and simultaneously at a few points in the model. The period of observations should be at least 14 days. This covers one neap and one spring tidal cycle. The spring tidal cycle gives the highest tidal range and thus it generates the largest velocity magnitude. The neap tide gives the smallest tidal range. For post-project monitoring purposes, it is recommended to simulate for both tides. Spring tide will show areas of high bed stresses indicating potential erosion while the neap will illustrate areas of deposition or sedimentation. Furthermore, pollutant dispersion characteristics differ between neap and spring tides.

The positioning of tide gauges is important. At least two is required and they should be situated at the extreme ends of the model area. If a third tide station is set up, it must be installed within the model area. This station can then be used for the model calibration and validation. Tide leveling instrument used automatically records the water level variations. The conventional type is the float method type but the pressure tide level recorder is more convenient and is gaining popularity. It is however crucial that accurate leveling of the tidal reading datum is done. Errors may introduce unpredictable results and will make the model very difficult to calibrate and validate. The tides observed are also compared to tidal observations or predictions at established tidal stations that are situated all around the Peninsular Malaysia and along the Sabah and Sarawak coastlines.

Current metering must also be carried out at a few stations in the model area. The current meters must be of the automatic recording type where they can be left to record continuously unattended over a certain period of time. This allows simultaneous time-series observation of current profiles and tide levels. The purpose of current measurement is mainly for calibration and validation. At least three current meter stations are needed. The current meter must be suspended at mid-depth and securely anchored and clearly marked. The tidal range in the area must also be considered when suspending the current meters at mid-depth. A point to note is to avoid busy shipping lanes and over popular fishing ground. The latter has been cause for concern when fishermen sometimes accidentally, and sometimes purposely, pick up or cut loose the current meters. This may result in not only losing expensive equipment but also valuable data. If this cannot be avoided, it is advisable to keep a close 24-hour guard on the instruments.

Bed samples are taken at various spots in the study area. The location and number of samples depends on the need and objective of the study. A grab sampler is used in deep areas (between 1 to 3m depths). Divers need to be employed at deeper stations. In shallow waters, bed samples can be manually collected. These samples were normally sieved to determine the bed material size distribution. This information is a useful parameter in sediment transport analysis. They are also visually examined for composition, texture and presence of specific materials. If a water quality analysis is required, samples must be collected and stored in special containers while being transported to the laboratory.

Wave height, length and period is recorded by installing wave riders in offshore locations. It is usually carried out over a long period of time to justify its deployment. As this is an expensive exercise, offshore wave condition is normally determined from shipboard wave observations that can be obtained from Jabatan Pengairan dan Saliran. Nearshore wave condition can be calculated using wave refraction analysis. However, wave impinging on offshore or coastal structures can be recorded using wave height and period recorder. Since these instruments are normally fixed to structures, they are not that expensive to maintain.

Wind data in coastal region may be recorded but it is adequate to use the annual data compiled by the Perkhidmatan Kajicuaca Malaysia from their stations all around Malaysia. The positioning of the data sampling stations on the map must be accurately marked. In situ plotting of the position of the stations is essential so that any mistakes can be rectified on site. Nowadays this can be done quite easily using portable GPS instruments. Usually, 2 or 3 positioning exercises are carried out to countercheck the results. It is not unusual to find that a current meter has drifted after a few days thus quick actions on site can be taken immediately if constant monitoring is done.

The data collection strategy depends on the purpose and expected model output but not less important, budget allocation play a role. More data does not mean better modeling output but rather the quality of data concerned. All too often, data were contaminated or blurred due to instrument mishandling and malfunctions or improper care during sampling. Having a large number of reliable and trustworthy data will greatly enhance the model calibration and thus the model results. However, if budget is limited, it is wise to plan properly and optimize the resources available.

CONCLUSION

This paper has discussed the use of computer models in coastal engineering application. It is clear that a model output is only as good as the technique used in solving the governing equation and in setting up the model. Assuming an established and well-proven model is used, the onus is on the user to make sure that the results obtained are reliable. In order to improve on this aspect, several guidelines were forwarded on achieving this objective. Proper technique for model setting up and data collection strategy were forwarded.

ACKNOWLEDGEMENT

The author wishes to thank Institut Kejuruteraan Pantai dan Lepas Pantai, Universiti Teknologi Malaysia for allowing the use of the model outputs.

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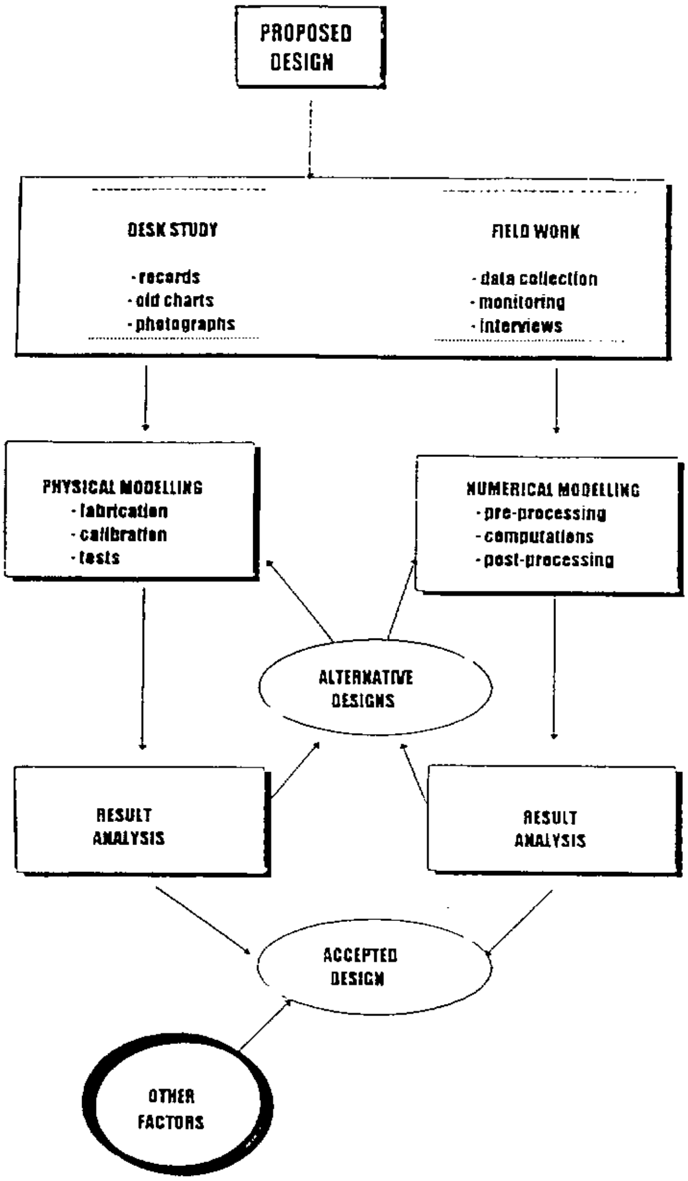


Figure 1 : The Role of Modeling in Coastal Engineering Design

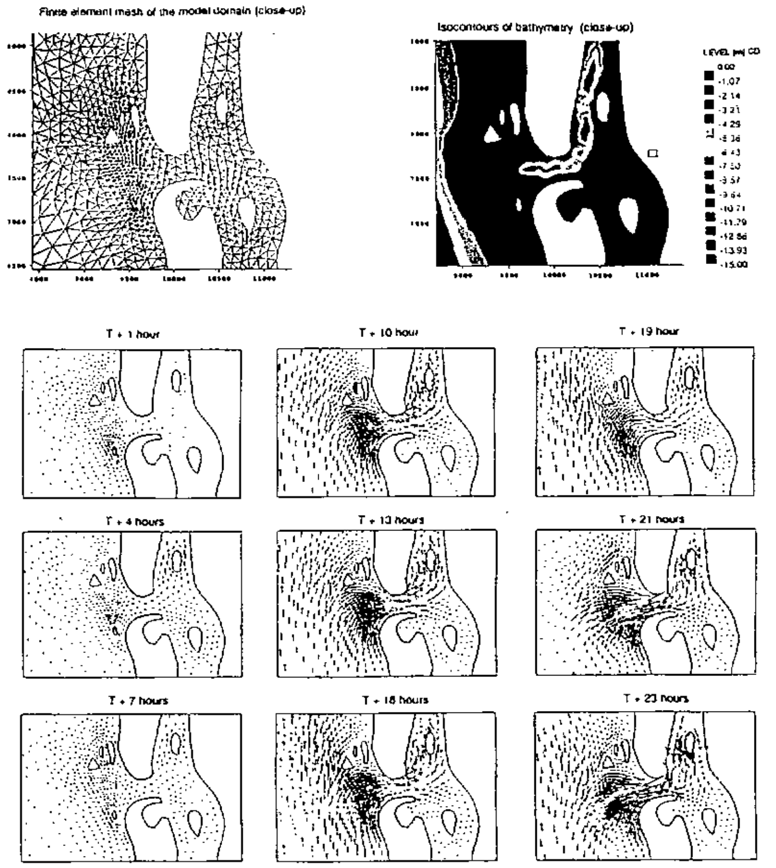
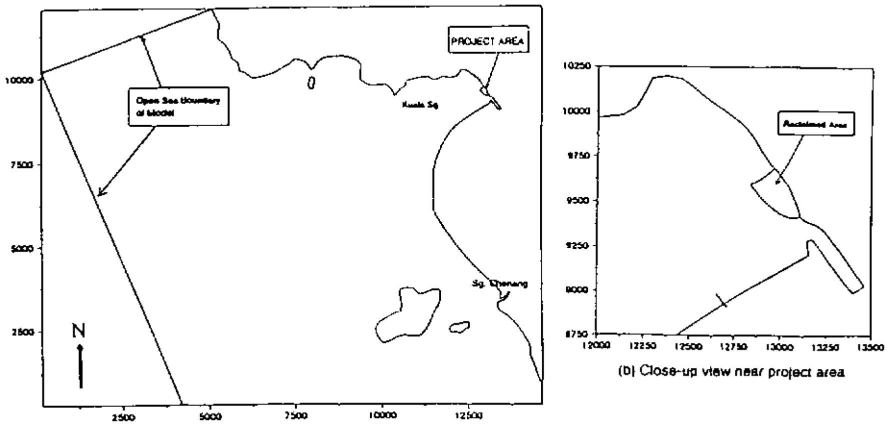
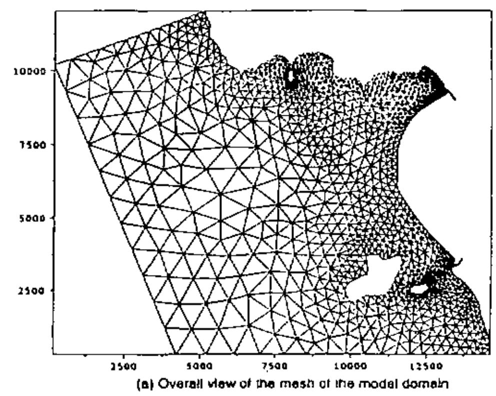


Figure 2 : Finite Element Triangulation, Bathymetry and Current Vectors at a River Inlet

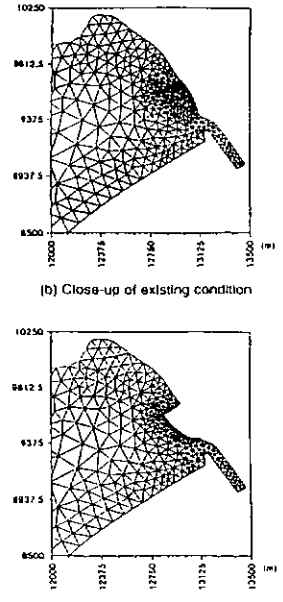


(a) Overall layout of the model domain

(b) Close-up view near project area



(a) Overall view of the mesh of the model domain



(b) Close-up of existing condition

(c) Close-up after reclamation

Figure 3 : Typical Model Layout with Close-up of Study Area and Associated Triangulation

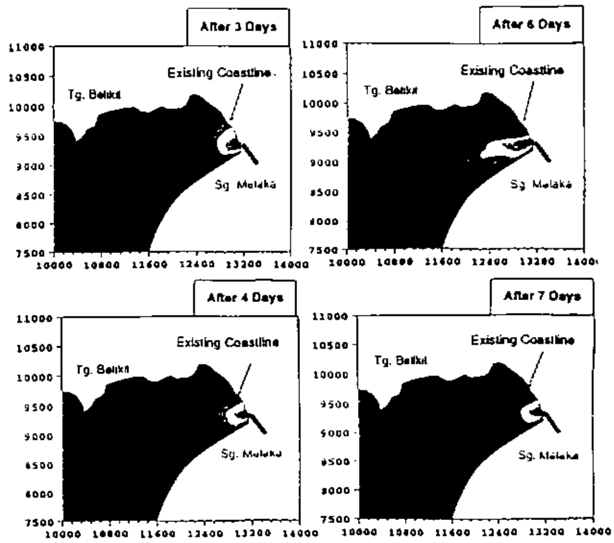


Figure 4 : Suspended Sediment Discharge From a Rivermouth

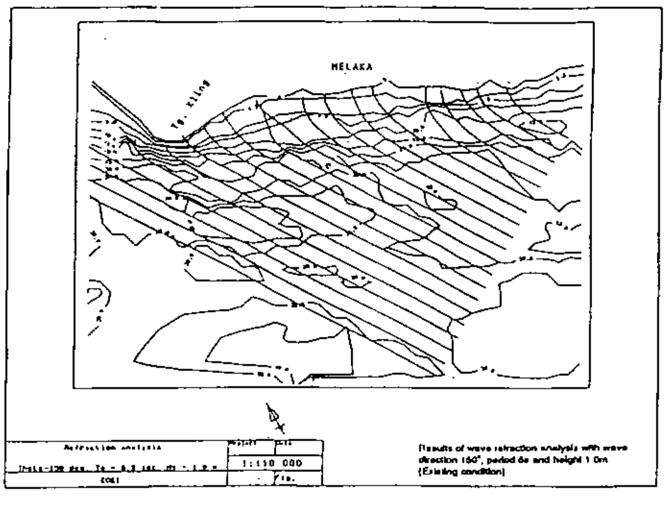


Figure 5 : Wave Refraction Modeling Output

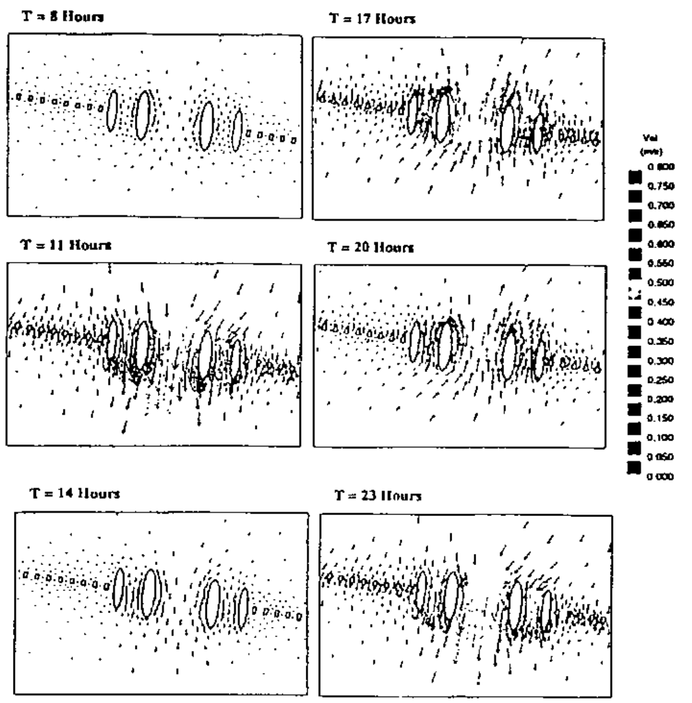


Figure 6 : Current Pattern Around Bridge Piers

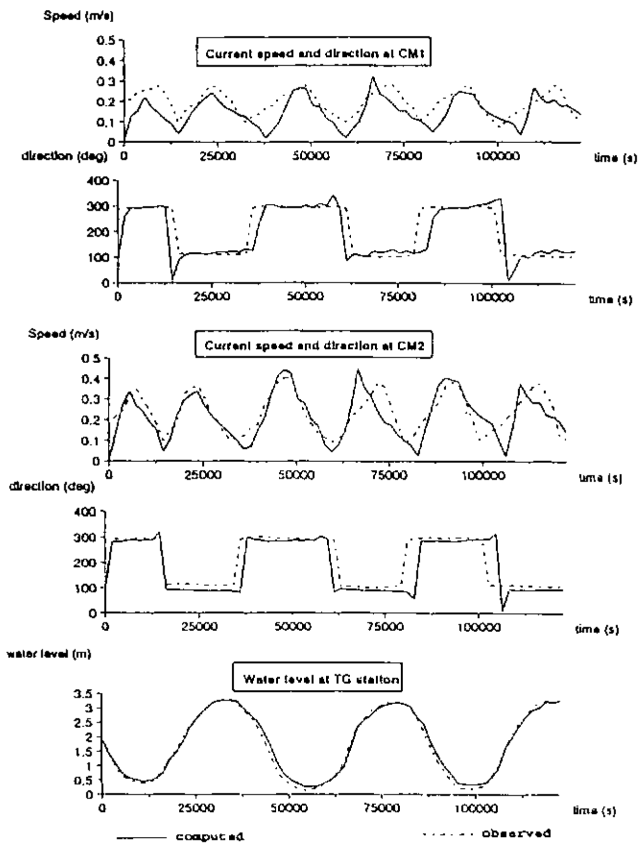


Figure 7 : Model Calibration Curves