Use of fast-time and real-time simulation in harbour design: The Dos Bocas case

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Abstract

In designing a new harbour such as the new planned oil- and container terminal in Dos Bocas, Mexico, the investigation of navigation safety, access channel, turning basins, position of buoys and marks, tug requirement and the estimation of the environmental window (wind, waves and current) are important issues, which require realistic modelling of:
- behaviour of representative vessels
- environmental conditions
- harbour layout

The paper addresses the Dos Bocas case and describes the set-up and use of fast-time and real-time simulators, the correlation between these and the recommendations and conclusions which were developed during the simulations.
Until recently, many harbours have been optimised with respect primarily to hydraulic considerations such as current, sedimentation and wave penetration with only secondary view to navigational problems. The main reasons for this are difficulties in quantifying the dynamic motions of vessels steered by human beings, and lack of integrated services from harbour designers with civil engineering background and captains and navigators with practical maritime experience. The result is that many ports are more difficult to navigate than would have been necessary if more consideration had been paid to the interdisciplinary aspects of hydraulics and navigation.

In fact, existing engineering design guidelines for water areas in ports and harbours (1,2 and 3) are based on previous real-life experience acquired through the navigation of ships in open and protected waters as well as construction and operation of port infrastructure. Very little information is derived from experimental analyses. Therefore, the guidelines advise that caution be taken by the designer and if possible, verification of results be performed by real life operation or use of reliable simulation techniques.

In recent years development of both fast-time and real-time simulators with more accurate and realistic mathematical models have provided the designers with a powerful tool. The DMI marine simulators are state-of-the-art within this area.

The use of ship manoeuvring simulators (real and fast-time) in the design of harbour areas (navigation channels and basins) provides a realistic tool for verification of navigation safety under specific environmental conditions and
infrastructure layout, thus preventing unexpected port operation problems for the future.

**Project Background**

Dos Bocas Oil, Industrial and Commercial harbour, in the Mexican State of Tabasco is a very ambitious port project sponsored by the Mexican Government, where fast-time and real-time simulation techniques were applied for design. This port was first conceived in the 70’s, and its construction began in 1980. However, macro-economical problems in Mexico forced the interruption of construction in 1985. Port facilities, including breakwaters, basins and docks were not completed. At that time the original project included two breakwaters, referred as East and West breakwaters with lengths of 2.9 km and 1.5 km, respectively. The design also included a 10-km access channel, as well as turning and docking basins with depths of 22 m. In addition, three "T" shaped piers attached to the East breakwater were also planned for exportation of crude oil in tankers as big as 250,000 DWT.

Without port facilities, since 1985 oil exportation in the area has been conducted through two offshore buoys. Ever since, annual operation time at these buoys has been lower than expected within a protected harbour, impacting negatively government’s sale revenues. This fact led in 1995 the Mexican government to re-consider its original plans of port development. With a project 18 years old and a significant progress on related engineering fields, a revision of the overall port development plan was first conducted. This revision was aimed at identify cost savings for completion of project construction, adopting state-of-the-art solutions in all infrastructure elements of the harbour, without ignoring previous construction progress. Furthermore, complementary economical studies combined with the engineering revision suggested that new areas of port activity such as Multi Use Terminals (MUT), commercial terminals and water-front industries would emerge from the basic exportation operations of oil in the area.

As a result, a more effective and updated layout of port facilities including breakwaters, access channel, turning basin and docking basins was achieved. The new proposal also identified two phases of construction so that port development would follow market and traffic forecasted trends. Phase One and Phase Two are illustrated in Figures 1 and 2, respectively. The most important navigation and protection elements included in phase One and Two are summarised in Table 1.
Fig. 1. Dos Bocas Phase One

Fig. 2. Dos Bocas Phase Two
Objectives

Having achieved a new port layout design, the use of ship simulation techniques was necessary for verification and evaluation of maritime safety. This evaluation included all phases of maritime operation including approaching and departure, tug boat assistance, manoeuvring and docking within the port areas. Wind, waves and currents had to be included in the simulations to reproduce realistic physical conditions as they would exist in real life during the operation phase of the project.

Real-time simulation was to evaluate the interior elements of the port in both Phase One and Phase Two, whereas fast-time simulation was applied to evaluate navigation along the 7.6 km long access channel in Phase Two. If the overall simulation phase showed that maritime safety was not achieved, changes including dimensions, position and orientation, had to be proposed for the respective infrastructure elements. In addition, these simulations would recommend manoeuvring procedures for port pilots when approaching, manoeuvring, docking and departing at the port. Finally, operation restrictions to preserve navigation safety had to be identified based upon a clear understanding of cause-effect relationships between physical conditions and expected maritime traffic.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Element</th>
<th>Dimensions (m)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Main Access Channel</td>
<td>1689</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Navigation Channel</td>
<td>1650</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Turning and Docking Basin (1 position)</td>
<td>650 x 450</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Inner Channel to MUT</td>
<td>1050</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>MUT Basin</td>
<td>576 x 450</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>East Breakwater</td>
<td>3478</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West Breakwater</td>
<td>1281</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jetties in MUT Navigation Channel</td>
<td>660 &amp; 690</td>
<td></td>
</tr>
<tr>
<td>Two</td>
<td>Main Access Channel</td>
<td>7600</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Navigation Channel</td>
<td>550</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Turning Basin</td>
<td>700</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>2 Docking Basin (125,000 DWT tank ships)</td>
<td>800 x 450</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>1 Docking Basin (250,000 DWT tank ships)</td>
<td>400 x 400</td>
<td>22</td>
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<tr>
<td></td>
<td>Inner Channel to Commercial Port</td>
<td>900</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Commercial and Industrial Basins</td>
<td>1,700 x 250</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>East Breakwater</td>
<td>3478</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West Breakwater</td>
<td>1281</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jetties in MUT Navigation Channel</td>
<td>660 &amp; 690</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of Navigation Elements in Dos Bocas Harbour
Fast-time simulator description.

The fast-time simulator at DMI is designed as a subsystem to the DeskSim see (4) environment which is the PC-based simulator at DMI. The mathematical ship model and environment model used in DeskSim is the same as used in DMI’s full-mission simulator DanSim. This ensures that the response of the ship model is state-of-the-art within ship simulators. For further information on DMI mathematical models see (5).

In normal DeskSim mode, the ship is controlled by the user by means of normal control equipment (rudder, engine telegraph, etc.) and running in real-time. But in fast-time mode the ship is controlled by the numerical navigator sub-system and the simulation is running as fast as the computer allows.

In the sections below, a description of the numerical navigator is given.

Navigator Model

The navigator model consists of the following modules, each of which is described in more detail in the following sections.

- State Estimator
- Track Planning module
- Track Following module
- Navigator Decision module

Fig. 3. The Navigator model
State estimator

The state estimator gives the navigator information about his position and speed relative to the planned track on request. The state estimator is in this project defined as a perfect state estimator with no interference from uncertainties or any type of noise. This means that when the navigator determines to estimate certain parameters he gets exact information without delay.

Track planning module

The track planning module is designed with the aim of copying the planning process done by a human navigator.

The planning performed by the navigator onboard the ship consists of a route drawn in the chart which starts at the departure position (and heading) and ends at the desired destination (and heading), planned speed along the route, and environmental conditions such as current and wind.

The planned route consists of a number of way points, mostly connected by lines. In restricted areas the waypoints can be connected by arches in order to make a controlled turn. The waypoints indicate positions where a course change is considered necessary.

The speed and direction of the current are looked up in a table at the actual time of arrival, and if the wind conditions are known, this information is written as well. The planned speed which is judged on the basis of the surrounding environment and the navigator's temperament is written in the chart.

In order for the navigator to be able to make a plan he has to have knowledge of the ship's manoeuvrability and its limitations. The primary knowledge the navigator uses during turning is that the drift speed increases and the forward speed decreases, i.e. the drift angle increases. After the turn is complete, the drift speed decreases and the forward speed increases again. The navigator also has knowledge of the maximum turn rate he is able to obtain at certain speed and how fast the rate can be obtained.

In the navigator's mind a turn is composed of an acceleration phase, a constant turn rate phase, and a deceleration phase. In the acceleration phase, the turn rate is increased from an initial value of zero. In the next phase the turn rate is held (almost) constant, either because the physical limit of the ship is reached or because a certain planned turn rate is reached. The turn is finalised by returning to zero turn rate.

In order to model how the ship behaves as a result of a sequence of turning and straight sailing periods, an internal model was made. It is the aim of the internal
model to reflect the navigators expectations of how the drift and forward speed are influenced during manoeuvring together with the effect of current and - as a result of that - how the ship track evolves in time.

How the ship track is planned by the navigator is dependent on his requirements for how safe and how efficient the route should be. The most efficient route is the one which takes the shortest time and would be the desired route on open water. However, in coastal waters or channels the planned route has to take account of the surrounding environment. If efficiency was to be discarded, one could expect a planned route which took the ship on an unnecessarily long journey. The desired planned route would be something in-between the most efficient and the most safe, i.e. a route, which is optimal in some sense. This is the basic assumption for the planning module and calls for the use of an optimisation tool and a proper object function which compromises between efficiency and safety while taking account of the surrounding environment.

The object function is a function of the proposed route which must satisfy the start and end conditions and the surrounding environment. The surrounding environment is modelled by a set of safety polygons which separates the “acceptable” areas from the “non-acceptable” areas.

Track following module

The basic idea of the track following module is that it should reflect the navigators way of following his plan. This means that the basic aspects of position observation with discrete intervals and adjustments of the ship parameters (heading command, rudder angle, handle setting) is included in the model. The track following module should thus be able to control the ship by following the planned track from the track planner and keep the ship within a small distance from the plan if no disturbances or navigator errors are introduced in the navigator module. The position observation and the controls can be applied at discrete time intervals determined either from a default time or from strategic time estimates of when a new state estimate is needed or from a random time with a certain mean and standard deviation.

The track following module has been made as a simple method of adjusting the ships approach velocity towards the track. This is done in two modes, one in the straight sailing mode and one in the turning mode. The correction is done by heading commands and Rate of Turn commands to the auto-pilot. (These commands could just as well be given to a helmsman.)

Navigator Decision Module

This is the central navigator decision maker. It determines what, when and how things are done in the whole navigator model.
During running of the navigator one has to determine when and how observations, actions and commands are made.

Observations are defined as an update of the following parameters and a part of the state estimator:

- ship position
- ship speed
- handle setting
- rudder angle

At present, all this information is considered present and correct when it is requested for.

Actions are defined as:

- calculate position relative to the track and other relevant track parameters (part of state estimator)
- calculate if track error is acceptable
- if track error is acceptable calculate correction to adjust track error and give appropriate command to helmsman and/or adjust machinery telegraph (part of track following)
- if track error is not acceptable, make a new plan.

The time intervals between the actions depend on the situation. At present, strategic time intervals are chosen in the method when sailing straight ahead. Otherwise, a default time determines when actions are taken.

Commands are defined as:

- Heading command (executed by helmsman or auto pilot)
- ROT command in a turn (executed by helmsman or auto pilot)
- Handle commands (executed by navigator)

The commands are in the present version planned to be made the very second where it is found appropriate to make a correction.

Fast-time simulator set-up and conclusions for approach channel.

Fast-time simulators are very powerful tools when designers etc. are to decide at important early stages of a project as was the case in the Dos Bocas project.

In this case the designers made an initial proposal for the access channel leading into the Dos Bocas harbour. The channel started 10 km off the coast followed a
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straight line and then made a 45 deg turn into the harbour. The designers had tried to use as much as possible of the natural depth at the side in order to limit dredging. This channel was supposed to be used by ship types up to 250000 dwt (see below).

The main concern was with ships departing the harbour as these are restricted due to their limiting draught. Ships arriving the port should cause no problem as they always arrive ballasted and as natural water depth are sufficient for these.

For the fast-time simulations the following ships were chosen. Main particulars are shown in Table 2.

<table>
<thead>
<tr>
<th>Ship number</th>
<th>Ship-type/loading condition</th>
<th>Lpp (m)</th>
<th>Beam (m)</th>
<th>Draught fore/aft (m)</th>
<th>Displacement (m$^3$)</th>
<th>Shaft Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3112</td>
<td>VLCC/loaded</td>
<td>310.0</td>
<td>56.0</td>
<td>20.0/20.0</td>
<td>270000</td>
<td>18.0</td>
</tr>
<tr>
<td>3113</td>
<td>Bulker/loaded</td>
<td>265.0</td>
<td>43.0</td>
<td>15.0/15.0</td>
<td>135000</td>
<td>13.6</td>
</tr>
</tbody>
</table>

Table 2.: Main particulars of ship models

Both models are true 6 degrees-of-freedom models.

Environmental Conditions

Current Conditions

Two current definitions were included in the simulations, one East-going and one West-going, both with a maximum current speed of 1.5 knots. Inside the harbour the current was zero and just outside the breakwaters, the current was perpendicular to the leading line into the harbour.

Wind Conditions

The simulations were made using a constant wind speed and direction for each run. Wind speeds from 15 m/s up 35 m/s and directions NE, N, NW were used as these are the most critical and common directions according to the local pilots.

Wave Conditions

Waves were included in the simulations where the random nature of wave height and period was modelled by the PM-spectrum with no directional spreading. Wave areas were defined in the environment so that inside the harbour a small wave height was used and outside the harbour the wave condition defined for the
particular run was used. The relation between significant wave height and period is taken from the ITTC-formulation:

\[ T_s = 12.09 \cdot \frac{H_s}{\sqrt{g}} \]

Wave heights (Hs) were ranging from 2.5 - 4 m, periods (Ts) ranging from 6.1 - 7.72 s and directions from NW, NNE as these are the most critical in the area.

**Water Depths**

The water depths used in the simulations were defined from the charts and surveys of the area received from the client.

**Fast-time simulations and conclusions**

A total number of 64 runs were performed with combinations of the above described environmental conditions. The simulations were started with ships in the middle of the harbour with a forward speed of 1 knot, which correspond to the condition just after the ship had left the berth and started to move forward. See fig. 4.

![Fig. 4 Plot of all 64 runs.](image-url)
All runs were analysed in four different locations (crossing lines) along the channel with respect to "speed when crossing the line" and crossing distance from mean position across channel". In addition use of rudder and engine were analysed.

The main conclusion of the fast-time simulations was that the channel design satisfies the demand for manoeuvring the ships safely along the channel.

The analysis of the speed reached at the entrance of the harbour showed that the distance inside the harbour used to accelerate the ship was sufficient to counteract a strong cross current outside the harbour.

The deterministic guidelines given in "Approach Channels - A Guide for Design" propose the maximum swept lane width to be less than 70 % of available channel width. The maximum swept lane width of all runs was found to be appx. 60 % of available channel width which - compared to the deterministic guidelines - was satisfactory.

An analysis of the manoeuvring effort made by the numerical navigator showed that - compared to the "Approach Channels - A Guide for Design" - for each run, the mean rudder angle, the standard deviation of the rudder angle, and the number of crossings of the mean rudder angle per time unit were satisfactory.

Real-time simulation

Real-time simulators are powerful tools for engineering purposes because they are capable of modelling realistic environment and vessels with a man-in-the-loop, which enable the designers to test out different layouts and situations in order to determine the best layout within the stipulated.

The simulations were carried out in DMI’s full mission simulator, which have a 360 deg. visual view. The bridge is a full version of a real bridge, with radars, electronic sea charts etc.

Next step was to evaluate the internal harbour layout for both phases of the proposed project of Dos Bocas. Phase one which was designed for tankers up to 100.000 dwt and containers up to 30.000 dwt. and phase two which was designed for tankers up to 250.000 dwt. and containers up to 30.000 dwt.

Of most concern in the Dos Bocas Port project was whether the turning basins and channels were sufficiently wide to provide the pilots with enough space to deal with the situation under critical conditions.
7 ships of different sizes and types were used during the simulations. See Table.3. The 7 ships (Tanker and Container ships) were all in the pool of ships that call Dos Bocas port.

<table>
<thead>
<tr>
<th>Ship number</th>
<th>Ship-type/ loading condition</th>
<th>Lpp (m)</th>
<th>Beam (m)</th>
<th>Draught fore/aft (m)</th>
<th>Displacement (m^3)</th>
<th>Shaft Power (MW)</th>
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<tr>
<td>3112</td>
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<td>56.0</td>
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<tr>
<td>3113</td>
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</table>

Table 3: Main particulars of ship models

Captains with more than 25 years of experience with the chosen ship types were conducting the ships during the simulations.

The environmental conditions were decided upon in order to create the most common conditions in the area and the worst conditions experienced in the area of Dos Bocas.

During the simulations it became clear that it was necessary to use tugs both for arrival and departure for the conditions simulated. Tugs with up to 6000 HP and 4000 HP was used. Tugs were connected to the ship either as pull tugs or as push tugs as recommended by the captains, who also gave orders on how to pull or push.

For Phase One the first thing to be tested was the availability of the new berth 1 for the tankers. This included the turning basin just in front of the berth and the channel leading up to the berth. It became clear that the channel leading up to the berth which was dredged to 16m proved to be sufficient for tankers up to 100.000 dwt. Due to the low speed it was proved that squat would cause no problem. For winds up to 15 m/s it was safe for 100.000 dwt to arrive and depart. For the 60.000 dwt the wind speed was 18 m/s.

The channel into the MUT for the 30.000 dwt. containers caused some problems due to the stopping distance available and the turning basin just in front of the entrance of the channel. A solution came up during the simulations as it was suggested to dredge some more at the “corners” of the link between the channel and the turning basin which resulted in a smoother turn into the basin.
Furthermore it was recommended to extend the width of the channel into the MUT by 25 m on each side in order to help after the sharp turn into the channel. This problem was more critical for arrivals than departures. It was proven that safe arrivals could be done in wind speeds up to 15 m/s due to the stopping distance and departures in wind speeds up to 18 m/s.

Waves up to 3.1 m and current up to 1 knot was tested and was proven to cause no problem for ship sizes used during the simulations.

Recommendations on buoyage was also suggested for safe navigation in the harbour.

Phase Two was tested with tankers up to 250,000 dwt. with departures and arrivals from both berth 1 and 3.
It was proven that the proposed design of access channel and turning basins was sufficient for winds up to 18 m/s. It was recommended though that dredging just inside the breakwaters on the south side would improve the safety of arrivals in high wind speeds, with ballasted ships up to 11 m draught.

Plots from real-time simulations see fig.5 for Phase One and fig.6 for Phase Two.
Conclusions.

Using fast-time and real-time simulations in combination during the design phase gives the designer the opportunity to choose between several proposed layouts in a fast and efficient manner, and to determine the optimum.

The fast-time simulations provide the designer with a large number of solid statistical data which give a clear idea of the viability of the various layout alternatives.

The human factor plays a major role during the real-time simulations. Real-time simulations give the designer a god understanding of the problems that captains experience when manoeuvring under extreme environmental conditions.

The case discussed in this paper illustrate that use of fast-time and real-time simulations in combinations can have profound consequences for the design and layout of a harbour. Several design aspects should be considered interactively with the hydraulic design process.

It is therefore recommended that fast-time and real-time simulations are used not only for verification but also as a design tool.
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