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Ichthys LNG Project, Australia:  
hydrodynamic modelling to inform management activities during dredging

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Abstract—The Ichthys LNG Project is a Joint Venture between INPEX group companies (the Operator), major partner Total and the Australian subsidiaries of Tokyo Gas, Osaka Gas, Chubu Electric Power and Toho Gas. Gas from the Ichthys Field (Fig. 1), in the Browse Basin offshore Western Australia, will undergo preliminary processing offshore to remove water and raw liquids, including condensate. The gas will then be exported to the onshore processing facilities at Bladin Point (Fig. 3) near Darwin via an 889 km pipeline. The Ichthys LNG Project (Ichthys Project) is expected to produce 8.4 million tonnes of LNG and 1.6 million tonnes of LPG per annum, along with approximately 100,000 barrels of condensate per day at peak. First production is scheduled to commence by the end of 2016.

The Ichthys LNG Project’s dredging programme was required to create a safe shipping channel and berthing area for LNG carriers through Darwin Harbour to Bladin Point. The overall purpose of the study was to determine where material liberated by the dredging activity would be transported to so that suitable monitoring, management and mitigation measures could be planned for. Critical to this was the development of a robust hydrodynamic model of Darwin Harbour and the surrounding area. This paper specifically describes the setup of the hydrodynamic model. A sediment transport model was also developed as part of the study.

I. INTRODUCTION

Darwin Harbour is located on the northern coast of Australia (Fig. 2). The Middle Arm Peninsula, within Darwin Harbour (Fig. 3), has been selected for an onshore processing plant of the gas extracted from the Ichthys Gas Field. The navigation channel cannot, however, accommodate deep-draft ships in its natural state and it is necessary to dredge the approach channel and berthing area in the immediate vicinity of the product loading area.

Within Darwin Harbour, there are extensive Mangrove habitats and coral is also present. The Operator is required to demonstrate to the local and national authorities that the dredging activities will not cause a significant impact to these important habitats. To that effect, numerical modelling studies were undertaken in order to predict the effect of the dredging on tidal flows, waves and sediment transport.

Figure 1. Location map showing the Ichthys Field in relation to Darwin.

Figure 2. Location map, also showing the model extent as an orange line.
HR Wallingford has provided support to the Ichthys Project since July 2009. During that time, extensive numerical modelling of potential and planned dredging programmes has been undertaken to simulate the dispersion of the fine material from the proposed dredging activity. A fine grained sediment transport model was used for that purpose, mainly driven by a hydrodynamic model. This paper presents only the TELEMAC-2D hydrodynamic model.

What started as a relatively simple model, relying on a few simplifying assumptions, has developed over the years into a complex, robust and accurate model that has been extensively calibrated and validated, using field data. This paper describes the final version of the hydrodynamic model and, as such, summarises all the steps that went into the development of the hydrodynamic model.

II. THE DARWIN HARBOUR MODEL SETUP

A. Extent

The Darwin Harbour model extends for over 325 km from the westernmost boundary to the easternmost boundary. To the West, it extends offshore, past Cape Fourcroy and Point Jenny, to approximately the 50 m contour and therefore entirely covers the Beagle Gulf. To the North, the hydrodynamic model extends to the southern coastline of the Melville and Bathurst Islands. To the North-East, it extends to Cape Don and Soldier Point, and therefore includes the whole of the Van Diemen Gulf.

The hydrodynamic model extent was initially defined as the (approximately) +5 m contour above mean sea level extracted from SRTM3 satellite data (refer sub-Section 0 for information on these data). The boundary was later refined using satellite imagery and vegetation maps to capture the sensitive inter-tidal and mangrove areas. Fig. 3 clearly shows this, where the orange line is the outline of the hydrodynamic model. This approach is conservative and was intended to include all regions prone to flooding.

The full model extent is shown in Fig. 2.

B. Resolution

Given the extent of the hydrodynamic model area, a mesh with spatially varying resolution was used. The mesh size varied from about 5 km in regions away from the harbour, in the middle of the Van Dieman Gulf, to 350 m across Darwin Harbour approaches and between 30 m and 150 m in areas of interest (e.g. mangrove areas). A resolution of between 75 m and 150 m was used in inter-tidal areas. Overall, the hydrodynamic model area was represented using approximately 161,000 nodes and 307,000 elements.

C. Seabed map

A digital elevation model of the seabed throughout the hydrodynamic model area, including inter-tidal and mangrove areas, was constructed by combining the different data sources available at the time of study, where superior data took precedence over data of lesser quality / resolution:

- LiDAR data covering the inter-tidal zones in the vicinity of Darwin Harbour, at 1 m and 5 m resolution. These data were generally used above -2 m MSL. SRTM3 topographic satellite data obtained from the U.S. Geological Survey at 90 m spatial resolution were used in areas not covered by the LiDAR data.

- Recent bathymetric survey data collected in 2010 and 2011 in Darwin Harbour, and other sensitive areas (e.g. Shoal Bay, Blue Holes). Bathymetric contours and spot heights from navigation charts covering the Beagle Gulf and Van Diemen Gulf were used otherwise.

Best judgement was used to extrapolate in areas where sparse or no data were available.

D. Friction map

In TELEMAC-2D the bottom roughness can be represented with a linear coefficient, a Chézy, Strickler / Manning coefficient, or using a Nikuradse roughness length. A Chézy formulation was used for this study, with a spatially-varying coefficient, dependent on the local water depth. Values between 30 m$^{1/2}$/s and 70 m$^{1/2}$/s were used throughout the hydrodynamic model area following the calibration process, the results of which are shown in Section 0. These values are within the range of expected bottom roughness coefficients.

The friction coefficients used in vegetated inter-tidal zones were originally based on a delineation of mangrove communities from satellite imagery and a description of the plants in the mangrove areas by the Department of Infrastructure, Planning and Environment [1].
Mangrove communities are often made up of obvious zones which run parallel to the shore. Each zone is likely to be dominated by one particular tree species, which has adapted to specific environmental characteristics. Generally a minimum of three zones are recognised, these being the landward zone, the seaward zone and an intertidal zone [3]. Fig. 4 shows a more complicated zonation pattern, which has been mapped in Darwin Harbour [2].

Many plant growth forms are associated with mangrove ecosystems including vines, grasses, shrubs, chenopods, sedges, forbs, palms, ferns and parasitic plants. Nine tree species coexist in the mangrove communities at the top end of the Northern Territory [1]. These species vary considerably in their appearance, adaptations to the coastal habitats and position in relation to the coast. Fig 5 and 6 show pictures of the Lumnitzera racemosa and Aegialitis annulata, two of the nine tree species found in the Darwin Harbour mangrove. The delineation of the mangrove communities from satellite imagery (see Fig. 7 for example)

Figure 4. Schematic profile of mangrove zonation in Darwin Harbour [2].

Figure 5. Lumnitzera racemosa (Black mangrove) [1]. One of the nine tree species found in the Darwin Harbour mangrove areas.

Figure 6. Aegialitis annulata (Club mangrove) [1]. Another tree species found in the Darwin Harbour mangrove areas.
identified a total of twelve communities, where one or more tree species are present.

A literature review was subsequently performed, which determined that the effect of the vegetation on the flows, as the tide rises and reaches the mangrove areas, was best represented based on [4].

In [4], the drag forces due to vegetation in x- and y-directions reproduced below as (1) and (2) are estimated as:

\[ F_x = C_d D_t m_t \frac{q_x \sqrt{q_x^2 + q_y^2}}{H} \]  
\[ F_y = C_d D_t m_t \frac{q_y \sqrt{q_x^2 + q_y^2}}{H} \]  

where \( C_d \) is the drag coefficient, \( D_t \) the density of trees per unit area \((\text{in} \ \text{m}^{-2})\) and \( m_t \) is the diameter of trees \((\text{in} \ \text{m})\). These were estimated based on pictures (to help determine a representative diameter for each species) and aerial photographs (to help determine a representative density for each species). In the following, \( D \) refers to the drag factor \( C_d D_t m_t \).

In addition to the drag forces, [4] accounts for the reduction in cross-sectional flow area due to vegetation by using a porosity factor [5]. Equation (3) below is based on this:

\[ P = 1 - \pi \frac{q_x m_t^2}{4} \]  

It was initially envisaged to use both a drag factor, \( D \), and a porosity factor, \( P \), in the hydrodynamic model to represent the mangrove areas. The application of (3), however, indicated that the reduction in cross-sectional area \((\text{or blockage})\) due to the presence of the vegetation (tree trunks) was less than 2%. Porosity was, therefore, ignored in the final model simulations.

The friction coefficient (in the form of a Chézy coefficient) was adjusted in the vegetated inter-tidal zones to account for the drag caused by the vegetation \((D \text{ factor from [4]})\). Although best judgement was applied in the characterisation of the vegetation parameters \( C_d, m_t \) and \( D_t \), and although the resulting friction coefficients are within appropriate physical ranges, however, there remains some degree of uncertainty in the friction coefficients as there is uncertainty associated with estimating the values of the vegetation parameters.

A sensitivity analysis to the value of the friction coefficient used for the mangrove in the hydrodynamic model was, therefore, conducted. This analysis indicated that varying the friction coefficient in these areas \((\text{from spatially varying 15-20 m}^2/\text{s Chézy values to a constant 30 m}^2/\text{s value})\) did not make a significant impact on the performance of the hydrodynamic model \((\text{RMSE values of the order of 0.01 m and 0.01 m/s})\). A representative value of 30 m\(^2\)/s was, therefore, chosen in vegetated inter-tidal zones that provided the best results during hydrodynamic model validation.

E. Tidal forcing

TELEMAC-2D is driven by currents and/or water levels. In this study, time-varying sea levels were applied along the offshore boundaries of the hydrodynamic model (Cape Fourcroy to Point Jenny and Cape Don to Soldier Point, Fig. 2).

These time histories were derived from hydrostatic pressure data recorded at these locations in 2010, at 6 minute intervals without interruptions for a period of over 45 days. The data were processed to infer water depths, assuming a seawater density of 1025 kg/m\(^3\), and using concurrent time-varying Mean Sea Level Pressure (MSLP) obtained at high resolution from the nearest available Australian Bureau of Meteorology (BoM) weather station.

The frequency and time span of the data were deemed suitable to perform tidal harmonic analysis. Tidal harmonic analysis seeks to break the overall tide into the summation of a number of simple and quasi-independent oscillations of varying periods, each corresponding to the tractive cycle of an astronomical disturbing force, called tidal harmonic constituents.

The amplitude and phase of a tidal constituent are defined by harmonic constants; they are unique for every location. Combined with the fixed rotational speed of that constituent, the harmonic constants allow the prediction of the contribution of that constituent to the overall tide in time. Adding up the effects of all the constituents at a given location enables prediction of the overall tide at any time in the future or past \((\text{refer [6] and [7]})\).

Tidal harmonic analysis was performed on the water depth time records derived at Cape Fourcroy, Point Jenny, Soldier Point and Cape Don to determine adequate boundary
conditions for the hydrodynamic model. The harmonics
analysis software used in this study was T_TIDE [8].

Water depths were then converted to sea levels relative to
MSL to drive the hydrodynamic model by reducing the water
depths using the mean sea level value derived from harmonic
analysis of the data. A vertical shift was also applied to the
sea level time histories predicted at Cape Don, Soldier Point,
Cape Fourcroy and Point Jenny, when appropriate, to
account for documented seasonal variability in Mean Sea
Level throughout the year. This was based on long-term tide
gauge observations (monthly average data) held by the
Australian Bureau of Meteorology (BoM) for Darwin station
IDO71064 up until April 2013 (blue dots in Fig. 8).

Time-varying sea levels were applied along the offshore
boundaries of the hydrodynamic model. Best judgement was
used to derive appropriate interpolation of harmonic
constants from the data obtained at discrete locations to
provide time-varying levels across the model boundaries.

F. Meteorological forcing

In addition to tidal forcing, the hydrodynamic model was
sometimes driven by additional wind forcing processes. This
part of the Northern Territory coast is subject to seasonal
influence of different wind regimes. The main wind regimes
may be summarised as follows:

- Trade winds, which blow with predominant direction
  East-South-East, characterise the Australian dry
  season from May to July. They can reach up to 15
  m/s.

- Westerly monsoonal winds, which are strong, rain-
  bearing winds, characterise the Northern Territory
  wet season from October to February. There are
  usually two or three major monsoon events during
  the wet season.

- Transitional periods between the ESE trade winds
  and the W monsoon occur in March to April and in
  August to October. There is no abrupt change from
  one to the other. For a period of several weeks light
  winds, interspersed by squalls, predominate [9].

When winds were included, they were applied as
temporally-varying but spatially constant fields, and taken
from the NOAA WAVEWATCH III® global wave model
data archive, in the absence of more suitable and site-specific
data.

The NOAA WAVEWATCH III® data are available at 3-
hourly intervals, covering the period between January 1997
and April 2013. The annual wind climate at point 12°S,
130°E at the entrance to the Beagle Gulf is presented in
Fig. 9 for information. In Fig. 9, sporadic high winds from
NE to E are noted. A finer (monthly) analysis indicated that
these conditions occurred in December and from March to
April.

III. CALIBRATION, VALIDATION AND VERIFICATION

The dispersion of fines associated with the dredging
activities is primarily governed by the prevailing
hydrodynamics. An effective hydrodynamic model is,
therefore, paramount to the accurate representation of the
advection and diffusion of material released in the water
column.

The hydrodynamic model was calibrated and validated
against observed current and water level data collected in
2008 in Darwin Harbour and in 2010 at the Blue Holes and
the spoil ground. It was later verified against more recent
data collected in 2012 and 2013 in the Darwin Harbour area.
Fig. 10 to 12 present some of the results of the calibration,
validation and verification exercise.

The comparisons made in Fig. 10 to 12 give confidence
in the predictions of the hydrodynamic model. The flow
characteristics are satisfactorily predicted at measurement
locations offshore in the Beagle Gulf, including at the
proposed disposal site and at the Vernon Islands area.
Agreement at the Blue Hole location, c. 20 km away from the
main area of interest, could be further improved should
highly resolved local bathymetry/topography data be made
available. In the current version of the model, the
representation of the Blue Hole was based on a simple
schematisation of the complex pool and terraces features.
The same can be said of the Upper East Arm location, Fig. 3, (results not shown here), where the model results were generally found to be less representative than at other locations in the model, though still reasonable.

The agreement of the predicted and observed traces in the Progressive vector plots (PVP) indicates that the residual current throughout the verification period is reasonably reproduced, both in direction and magnitude in Darwin Harbour (Fig. 12). At the spoil ground, the ENE flows are generally more closely reproduced than the WSW flows. This explains to some extent the discrepancies shown in the PVP between observations and predictions (Fig. 12), where the predictions indicate a more substantial southward flow component than the observations.

The residual velocities for both observations and predictions were derived from the verification period and compared in Table I.

<table>
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<tr>
<th>TABLE I. RESIDUAL CURRENTS COMPUTED FOR THE VERIFICATION PERIOD</th>
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The agreement was also assessed quantitatively by computing Root Mean Square Error (RMSE) statistics on both velocity and water surface elevation. These are summarised in Tables II and III. Overall the performance of the hydrodynamic model is satisfactory and it is expected that its results will, when used in the dispersion study, provide a good estimation of the dispersion patterns of dredged material both within Darwin Harbour and offshore in the Beagle Gulf.

<table>
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<tr>
<th>TABLE II. PERFORMANCE OF THE HYDRODYNAMIC MODEL (CALIBRATION/VALIDATION AGAINST 2008 AND 2010 OBSERVED DATA)</th>
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<td>RMSE on levels</td>
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<td>RMSE on speeds</td>
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The residual velocities for both observations and predictions were derived from the verification period and compared in Table I.

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<th>TABLE III. PERFORMANCE OF THE HYDRODYNAMIC MODEL (VERIFICATION AGAINST 2012 OBSERVED DATA)</th>
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<td>RMSE on levels</td>
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<td>RMSE on speeds</td>
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REFERENCES

Figure 11. Current speed in Darwin Harbour (2008), at Blue Hole and the spoil ground (2010-2011).

Figure 12. Tidal ellipse and Progressive vector plot in Darwin Harbour and at the spoil ground (2012).