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# TECHNICAL REVIEW OF FINAL 3D MODELLING - POTENTIAL EFFECTS OF MARINE STRUCTURES ON SITE HYDRODYNAMICS AND SEDIMENTATION FROM THE CONSTRUCTION OF THE PACIFIC NORTHWEST LIQUEFIED NATURAL GAS TERMINAL

## 1.0 Context

Pacific NorthWest Liquid Natural Gas Ltd. (PNW LNG) is proposing to construct a large scale liquefied natural gas (LNG) export terminal near Prince Rupert, BC, within the Skeena River estuary (herein after referred to as the 'Project'). The Project would involve the development of combined suspension bridge and pile trestle from Lelu Island to a terminal berth, a materials offloading facility (MOF), pioneer dock and access bridge to Lelu Island.

The proposed suspension bridge would connect Lelu Island and Agnew Bank, approximately 1,500 m to the northwest of Flora Bank, and would be supported by two isolated in-water supporting structures, referred to as the Southwest (SW) Tower and the Anchor Block. From the seaward end of the bridge, a trestle supported by steel pilings would continue for approximately 1,300 m to a berth and traffic deck.

On April 8, 2013 the Canadian Environmental Assessment Agency (CEAA) issued a Notice of Commencement that they had begun an environmental assessment pursuant to the Canadian Environmental Assessment Act (CEAA 2012) for the PNW LNG project located on Lelu Island.

The Environmental Impact Statement (EIS) and Addendum submitted by PNW LNG to the Canadian Environmental Assessment Agency on 28 February 2014 and 12 December 2014, respectively, provided information with regard to potential effects of marine operations and marine structures upon the sea bed and habitat at Agnew and Flora Banks. The Addendum also provided detailed responses to Information Requests posed by the Government of Canada in regard to sediment deposition, and included a report that provided a sediment transport and deposition analysis. This report was based on work that utilized 2D models and was conducted by PNW LNG's marine engineering consultant, Hatch Ltd.

On February 23, 2015, PNW LNG received a new Information Request from CEAA requesting additional 3D hydrodynamic and sedimentation modelling. A Terms of Reference was developed to guide the additional assessment. The Proponent responded to the February 23rd CEAA request by submitting a report dated May 5, 2015 entitled "3D Modelling of Potential Effect of Marine Structures on Site Hydrodynamics and Sedimentation" (Hatch, 2015a).

Fisheries and Oceans Canada (DFO) Science Branch had provided informal advice to DFO Fisheries Protection Program (FPP) on previous drafts of baseline and post-construction modelling undertaken by PNW LNG to assess the potential effects of marine operations and marine structures on the sea bed and habitat at Agnew and Flora Banks. Following the Proponent's submission of the May 5, 2015 report (Hatch, 2015a), FPP placed a request to Science Branch to provide a formal technical review of PNW LNG's draft 3D baseline and post-construction hydrodynamic modelling. A Canadian Science Advisory Secretariat (CSAS) Science Response (DFO, 2015) was developed in response to this request from FPP. The

CSAS Science Response (DFO, 2015) outlined primary areas of concern with respect to the Hatch (2015a) 3D modelling report. These concerns were conveyed in a DFO response (June 2, 2015) to CEAA.

On June 2, 2015, PNW LNG received notice from CEAA that they had not satisfied the requirements of the Information Request #2, noting that the technical reviews provided by Natural Resources Canada (NRCan), and DFO, "indicates that their expert advice and direction to PNW in conducting its modelling work was not sufficiently taken into consideration, which has resulted in a lack of information". CEAA indicated to PNW LNG that their conclusions needed to be substantiated by further rigorous and thorough modelling results. CEAA informed PNW LNG that additional information was required before they could complete their environmental assessment report. Five key concerns regarding 3D modelling were identified in the June 2, 2015 CEAA correspondence. These were itemized as follows:

- Concerns regarding the wind and wave input forcing fields used to drive the 3D model.
- Concerns with the modelling of extreme storm events.
- Concerns with the modelling of flows in proximity to large structures (the Anchor Block and SW Tower).
- Concerns regarding the long term simulations and use of time-averaged forcing inputs to drive the model.
- Concerns regarding model outputs related to sediment transport.

PNW responded to CEAA's June 2, 2015 Information Request with submission of a report dated November 10, 2015 and entitled "Pacific Northwest LNG 3D Modelling Update - Supplemental Modelling Report" (Hatch, 2015b). DFO FPP is now requesting that DFO Science review PNW LNG's final submission of modelling of potential effects of proposed structures to Flora Bank and Agnew Bank areas in response to CEAA's Information Request and provide advice regarding the following:

1. Assess whether the five key concerns as outlined above have been addressed with sufficient accuracy and adequacy to facilitate an evaluation of PNW LNG's conclusions.
2. If the information and model results from PNW LNG are found to be sufficient; evaluate the validity of PNW LNG's conclusions, based on information and results as presented in the Supplemental Modelling Report.

This Science Response Report results from the Science Response Process of December 2015 on the Technical Review of final 3D modelling - potential effects of marine structures on site hydrodynamics and sedimentation from the construction of the Pacific Northwest Liquefied Natural Gas Terminal.

## 2.0 Analysis of Supplemental Modelling Report

This section provides a review of the Supplemental Modelling Report (Hatch, 2015b), with respect to the five concerns raised by CEAA over the modelling work presented in the earlier report (Hatch, 2015b), to address question 1 above. For each of these concerns, background information is provided and the response of the Proponent is summarized. In each case, an assessment is made on whether the work presented in the Supplemental Modelling Report (Hatch, 2015b) is adequate and of sufficient accuracy to allow an assessment of the impact of the Project on Flora Bank. In Section 3, key results are highlighted to assist DFO Fisheries Protection Program in making its assessment of the Project. The concluding section summarizes and recommends possible mitigation measures that DFO Fisheries Protection Program may wish to consider.

## 2.1 Wind and wave forcing inputs

### 2.1.1 Background

To examine the potential impacts of the Project on Flora and Agnew Banks, PNW LNG implemented a regional hydrodynamic model based on the Delft3D model (Deltares, 2014a and 2014b). This model is suitable for a representation of the hydrodynamics of flows over the project site, including the simulation of wave-driven currents (using the Simulating WAves Nearshore [SWAN] wave model) and changes in bottom morphology associated with sediment deposition and erosion. The regional model is driven by surface wind forcing and, at its lateral open boundaries, by incoming waves (swell) from the Pacific. An earlier DFO technical review of this modelling (DFO, 2015) questioned the approach taken to specify these forcings of the regional model, which, it was argued, would introduce unnecessary errors. Specifically, the following was deemed inadequate:

1. Use of wind data from a single buoy to specify the wind forcing over the entire regional domain, leading to a uniform wind field. It was suggested that use of gridded wind products was more suitable as this would allow the specification of realistic, spatially variable winds over the region.
2. Specification of uniform wave information at the outer boundary of the model, based on data from a single buoy. It was noted that “measurements at a single point cannot represent the variability of the wave field along the entire outer boundary of the wave model regional grid domain.” It was suggested that using available gridded products to specify the wave forcing at the boundary would reduce unnecessary errors and improve the simulations

### 2.1.2 Proponent’s revisions

The work reported in the Supplemental Modelling Report now makes use of a gridded wind product to provide spatially variable wind fields that are applied to drive currents and locally generated waves in the regional model. The report mentions that four different re-analysis products were considered to allow for the wind forcing over the model domain. Wind forcing from the Climate Forecast System Reanalysis (CFSR) Version 2 was selected to drive the model as this wind product had the finest spatial resolution and most complete coverage of the four gridded wind products that were considered. A comparison of the resolution of the four datasets is given in Appendix C, Figure C1, to support the Proponent’s selection of CFSR.

In addition to the revised wind forcing, the regional model is now driven at its lateral boundaries by spatially variable data on offshore waves. Two data products were considered: WAVEWATCH III®, a standard product made available by the National Oceanic and Atmospheric Administration of the United States Dept. of Commerce, and re-analysis wave data from the European Centre for Medium Range Weather Forecasting (ECMWF). WAVEWATCH III® was selected as it offered superior spatial resolution. Water depths in wave model simulations have been informed by estimates from the flow simulations.

### 2.1.3 Assessment

The wind and wave input forcings that have been incorporated in the model to produce the results presented in the Supplemental Modelling Report represent a clear improvement over previous work; they conform to the peer-reviewed scientific literature for the forcings to be used in a regional model. Accordingly, DFO assesses that the concern raised by CEAA in this regard has been addressed adequately and with sufficient accuracy by the Proponent. Simulations with the revised wind and wave forcing compare somewhat more favourably relative to previous simulations with respect to wave observations collected at a buoy deployed by PNW near the Project site. This improvement is due primarily to the use of spatially variable winds. However, for the observations that were collected at the PNW buoy, conditions were sufficiently benign that offshore waves appear to have relatively little impact at the Project site; for conditions such as the 50-year and 100-year extreme storm events (next section) a larger impact of offshore waves at the Project site is expected. A comparison with winds measured at buoys in Hecate Strait and Dixon Entrance showed very good agreement with the CFSR winds (Figure C-2). This is not surprising since it's very likely that winds from these buoys were assimilated into the re-analysis product. The report mentions that the CFSR winds were "improved locally using assimilation of Holland Rock winds with equivalent duration of 90 minutes." The extent to which this was necessary is uncertain since Holland Rock winds are probably already assimilated into the CFSR dataset.

## 2.2 Modelling of extreme storm events

### 2.2.1 Background

The potential impact of the proposed marine structures on Flora Bank during extreme weather events is an important consideration. In fact, under a changing climate, conditions may vary and extreme events with long return periods must be examined carefully. DFO (2015) found that the modelling of storm events presented in Hatch (2015a) was inadequate with respect to the intensity, duration and direction of the storm events given consideration. Specifically, the review concluded that

*"The analysis does not adequately consider an extreme storm for the 50-year return period, or an appropriate set of 50-year extreme storms, thereby underestimating the potential impact of the installation of marine structures on the surrounding environment. Although the Proponent does estimate the 50-year and 100-year winds at the Holland Rock buoy … several of the other conditions needed to estimate 50-year extreme storm impacts are scaled back or not explored. In particular, the analysis only considers a storm propagation direction that orients the marine structures downstream from Flora Bank, thus making it essentially impossible for the marine structure to impact Flora Bank."*

DFO (2015) indicated that a careful examination of storm events required the following:

*"The orientation of the artificial case should have several scenarios, including the cases where the waves pass Flora Bank first, then the marine structures second; and vice versa, with wave hitting the marine structures first, then Flora Bank second, etc. … The extreme storm cases should also consider storms where uniform winds are blowing at various angles with respect to the marine structures, Flora Bank, and Agnew Bank, and holding steady for at least half a day, or more, and include simulations with, and without, marine structures to see the full effects of the marine structures on the surrounding region. Model runs should show the full possible effects. Winds should be at the 50-year return level, at least, and ideally also include 100-year return levels."*

### 2.2.2 Proponent's revisions

Appendix G of the Supplemental Modelling Report discusses the approach taken to construct a set of synthetic storm events. Of the four cases considered, three have the marine structures upwind of Flora Bank with wind directions varying from northwest, west and southwest. The fourth case has the wind from the southeast. In each case the magnitude of the wind forcing is specified according to an estimated 50-year return period that is based on a 21-year record of wind measured by Environment Canada at the nearby Holland Rock Station. The synthetic storm is given a Gaussian time dependence with an overall duration of 11 days, and an e-folding time scale of about five days. Wind directions are held constant over the entire storm duration. The storm cases are chosen to coincide with a period of spring tides, thus allowing a combination of strong tidal flows and strong wind and wave driven currents.

### 2.2.3 Assessment

The synthetic extreme storm case developed in the Supplemental Modelling Report (Appendix G) meets the requirements stated in DFO (2015) for the specification of an extreme storm event. In addition to specifying winds of sufficient intensity, a conservative approach has been adopted in which the duration of the synthetic storm is substantially longer than any storm measured in the 21 year record of winds at the Holland Rock buoy. Thus, the waves generated by the storm will not be limited by duration. As suggested in DFO (2015), multiple directions for the wind have been specified such that in the different cases the proposed marine structures are situated either upwind or downwind relative to Flora Bank. Thus, there is inclusion of long-fetch swell waves that can be generated by intense cyclones in the Northwest Pacific, propagating towards the Flora Bank area from the Northwest. DFO assesses that the synthetic storms specified in the Supplemental Modelling Report to examine the response to an extreme weather event are sufficient and that this concern raised by CEAA has been addressed adequately.

## 2.3 Modelling of flows in proximity of large marine structures (Anchor Block and SW Tower)

### 2.3.1 Background

The project advanced by the proponent requires the installation of marine structures that extend through the water column in proximity of the northwest flank of Flora Bank. As noted earlier, the Project consists of a bridge supported by the SW Tower and the Anchor Block, as well as a trestle supported by a set of pilings. As noted in DFO Science Response 2015/027 (DFO, 2015), the SW Tower and the Anchor Block are the largest, most substantial structures; the modelling work presented in the 3D Modelling Report of May 5, 2015 (Hatch 2015a) suggested that these structures would produce the largest perturbations to the natural flow regime of the region.

Hatch (2015a) presented modelling work in which the marine structures (the Anchor Block, the SW Tower, and the series of trestle pilings) were represented within the regional Delft3D-Flow model as ‘porous plates’ that exert drag on the flow. This representation was accepted in the DFO review as a reasonable approach for the ensemble of trestle supports. (Further discussion of the trestle supports is given below.) However, the DFO review was critical of using porous plate representations of the SW Tower and Anchor Block. Specifically, the DFO review mentioned the hydrodynamic response that is expected in proximity of these large structures:

*“… flows impinging on such large structures will be blocked on the upstream side and accelerated along the sides of the obstacle. At the trailing edge there will be boundary layer separation and a turbulent wake in the lee of the structures. Given the proximity of the proposed structures to Flora Bank, the jet-like flows and vortices that will be shed in the lee of the structure can be expected to impinge on the sides of the Bank during flood tide. There is potential for these energetic flows to scour the Bank.”*

It was noted that the porous plate representation of the large structures was unlikely to produce an accurate representation of the expected changes to the hydrodynamic regime:

*"The relatively coarse resolution of the model (which necessitates the porous plate parameterization) is problematic for modelling the effect of the two large structures (the anchor block and the tower), and it is far from clear whether the effects of these structures are adequately represented. In particular, it is likely that the model is unable to adequately resolve the strong flows and shear generated in the lee of the structures. The turbulent flows and vortices that will be shed in the lee of the anchor block and tower are probably absent in the simulations, and the jet-like separated flows are bound to be more diffuse than in reality. All of this is likely to bias the results to underestimating the effects of these large structures."*

Lastly, to overcome this difficulty, it was mentioned in the DFO review that:

*"The obvious remedy for these problems would have been to conduct simulations that are of locally much higher resolution (perhaps in a nested model) in which the marine structures and turbulent flows are explicitly resolved."*

### 2.3.2 Proponent's revisions

In response to the critique outlined above, the Proponent implemented high-resolution, two-dimensional models for the regions in proximity of each of the two large structures. The MORPHO modelling system (Kolomiets et al 2014) was selected to simulate fine-scale physical processes around the proposed SW Tower and SW Anchor Block. Boundary conditions for these high-resolution models were extracted from the coarser resolution regional Delft3D model. MORPHO allows for wetting and drying of the seabed which is important for Flora Bank. The model uses an unstructured grid and was implemented with a variable lateral resolution that is finest immediately adjacent to the structures (~1.5 m grid size), and becomes substantially coarser with distance, increasing to approximately 200 m near the boundaries of the fine resolution domain.

The Supplemental Modelling Report and the accompanying video animations provided results from a set of simulations with the high-resolution models. These simulations included high-resolution model runs of the Anchor Block and SW Tower for a set of three different cases:

1. Sea surface elevations and currents driven by tides and freshet river discharge for a 28-day simulation period
2. As in (a), but with only tidal forcing
3. Tides and storm currents due to wind/waves from the west (270°N) for a simulated 50-year storm event

There were also sensitivity tests provided by the Proponent that examined the influence on the main results of variations in sediment grain size, changes due to the introduction of scour protection about the structures, and a change in the shape of the SW Tower from the basic rectangular shape to a circular shape.

Generally, results from these simulations show the modifications to the flow structures anticipated in DFO (2015). Specifically, this includes the formation of jet-like flows on the sides of the structures that impinge locally on the side of Flora Bank during a flood tide. As well, vortices of alternating sign are shed in the wake of the structures that subsequently propagate over the bank on flood tides. This response is similar to a von Kármán vortex street; the frequency of oscillation of the flow in the lee of the structures appears to be consistent with this interpretation (Appendix - Technical Notes for Section 2.3).

The high resolution simulations show that some scouring of the bottom sediment at the margin of Flora Bank occurs in response to the flows that develop in the lee of the structures during flood tides. This is in contrast to the previous results given in Hatch (2015a) that were based on the porous plate representation of the large structures. The latter failed to indicate any scour of Flora Bank associated these structures (e.g., Figures 7.4 to 7.7, Appendix B, Hatch Ltd 2015a). A fuller discussion of the important results from the high resolution modelling is included in Section 3 of this review.

### 2.3.3. Assessment

The new high-resolution simulations represent a clear and substantial improvement over the previous modelling of the flows in the vicinity of the two main structures. Specifically, they directly address the criticism of the representation of these structures as porous plates within a coarse resolution grid. The high resolution simulations display the essential physical processes that are expected to occur as flows encounter large marine structures. As such, simulations with the high-resolution models provide a credible basis for assessing the changes to the hydrodynamic regime introduced by these structures. They also form a basis for assessing the impact of these changes on sediment erosion, dispersal and deposition. In addition, the high resolution modelling now allows an investigation into the effects of changing the shape of the structures and the installation of scour protection.

Still, some caution is required to interpret the results from these simulations. The coarsening of the grid resolution with distance from the structures likely leads to an increase in the implicit numerical diffusion of the model. Accordingly, the vortices that are shed by the model are likely to be subject to such diffusive effects, and will be dissipated more quickly than if the fine resolution had been maintained over the entire high resolution grid. This may have an impact on the distance over which the eddies can transport sediments that are suspended by the flows near the structures. In particular, scaling arguments (Appendix - Technical Notes for Section 2.3) suggest dissipation of eddies through bottom friction on a length scale of about ~1000 m, while the simulations show eddies dissipating over a somewhat shorter scale. Numerical diffusion may be the source of this discrepancy.

## 2.4 Long-term simulations

### 2.4.1 Background

An objective of the Hatch (2015a) 3D modelling study was to examine the extent to which the Project would lead to long term morphological changes to Flora Bank by modifying large-scale flow and transport processes. Simulations based on the Delft3D model were reported that extended for duration of 134 days and included a morphological acceleration factor (MORFAC) of 13.5. Since the morphology may evolve slowly, this factor is used to avoid long, computationally costly integrations of the hydrodynamics. This is accomplished by scaling the fluxes of suspended sediment between the overlying fluid and the sea bed by an acceleration factor, MORFAC. The simulated morphological evolution is then said to represent the expected changes over a period of time given by product of MORFAC and the actual duration of a given simulation. In this case, the simulations were taken to represent morphological change over 13.5 times 134 days, that is, 5 years.

DFO (2015) raised several concerns with regard to the tidal and wind forcing and the freshwater discharge from the Skeena River that was applied in the hydrodynamic simulations with MORFAC > 1. In particular, rather than including the actual tidal forcing, the simulations included only a ‘representative tide’ that eliminated the spring-neap fortnightly modulation of the tides. The winds and waves were averaged over 7 day intervals, and the annual cycle of river discharge was compressed into a 26.9 day period. It was noted in the review that:

*“The weekly averaging the winds and waves eliminates the peaks in these fields associated with the passage of storms, while use of a representative tide eliminates the largest tidal currents*

*associated with spring tides. As a result, the likelihood of exceeding the critical threshold for sediment suspension and transport is underestimated in the model. As well, elimination of neap tides reduces the likelihood of meeting the threshold for sediment deposition."*

In addition, DFO (2015) noted that the compression of the annual cycle of river discharge was highly problematic. As a result,

*"The volume of freshwater and amount of suspended sediment discharged from the Skeena River into the coastal ocean is severely underrepresented in the model. This will lead to an underestimation of the buoyancy-driven circulation, as well as of the total suspended solids (TSS) in the water column."*

### 2.4.2 Proponent's revisions

A set of new simulations with the Delft3D regional model is presented in the Supplementary Modelling Report (Hatch , 2015b). For these cases the forcing provided by tides, winds, waves, and river discharge varies continuously, without the time averaging used in Hatch (2015a). For these new cases, referred to in the report as the 'time series simulations', no morphological acceleration has been applied (i.e., MORFAC is set to unity). A number of different cases are described. There are three simulations of relatively long duration. One extends for one year, covering the time period September 2012 - September 2013, and has 1-hour coupling between the flow and wave modules. Two additional runs have 3-hour wave-flow coupling which is less computationally demanding, and cover the periods, September 2012- September 2013 and May 2013 – May 2014. These simulations capture the annual cycle, including a period of winter storms, as well as a freshet period for the Skeena River discharge. There are also shorter simulations of 3-4 months for the winter storm and summer freshet periods.

The proponent has improved the regional ocean modelling by increasing the number of vertical layers in Delft3D from 5 to 10 to address concerns about the simulation of the salinity and stratification in the vicinity of Flora Bank (Appendix E). They have also improved the comparisons between the observed and modelled currents by expanding the time period used for the comparison in Porpoise Channel, by including data from Inverness Passage, and by using quantitative metrics for the comparisons (Appendix F).

### 2.4.3 Assessment

As requested in DFO (2015), the new long-term simulations make use of continuously varying forcing, and no longer use weekly-averaged winds and waves. Results from these simulations are now more credible than the previous cases presented in the May 5 report. DFO assesses that the concerns expressed in DFO (2015) over the questionable averaging of the wind and wave forcing, and the compressed record of freshwater discharge from the Skeena River, have been addressed adequately. In addition, by correcting the representation of the discharge from the Skeena River, concerns have been alleviated over the discharge of suspended sediment from the river.

Consideration of the Figures in Appendix F shows that the uncertainty in the peak current speed relative to the observations in Porpoise Channel and Inverness Passage is about 20%. The material in Appendices J and K and the model inter-comparison of Chen et al. (2013), suggests that the uncertainty in the current speeds over the bank (where there are no observations) is in the range of 20% - 40% (this applies to both the regional model and the high resolution model).

Overall, the uncertainties in the currents are consistent with the expectation in the international community that in situations dominated by currents the sediment transport quantities, such as erosion and transport rates, are expected to be accurate to within approximately a factor of 2

(NRCan's Research Scientist, pers. comm., 2015). Note that a 40% uncertainty in currents means a factor of 2 uncertainty in the bottom stress.

The regional ocean model simulations are useful for assessing the pre-construction conditions and the potential impacts of the trestles. These simulations have insufficient horizontal resolution to properly assess the potential impacts of the two large marine structures: the SW Tower and the Anchor Block.

DFO notes that no morphological acceleration has been included in the year-long simulations; therefore these cases do not model potential changes occurring on multi-year time scales. A review by NRCan has focused on the regional modelling and has determined that "the impact of the marine structures on currents, waves, sediment transport, and seabed morphology for various seasonal and storm conditions has been modelled with acceptable certainty."

## 2.5 Model results on sediment transport

### 2.5.1 Background

In an earlier technical review, NRCan raised concerns regarding model results on total suspended solids (TSS) and sediment transport. More specifically, it was recommended that "sediment transport rate and direction" as well as "net sediment transport flux and direction, and net erosion and deposition rates and distribution patterns" be included in the analysis of the model results. In addition, concerns were raised about the underestimation of TSS by the model. Finally, it was suggested that conclusions related to the effect of the marine structures on TSS are not supported by the model results.

### 2.5.2 Proponent's revisions

Appendix K on sediment mobility and transport was added by the Proponent in response to the above concern. It provides a detailed look at the sediment transport calculations and presents estimates of the fraction of the time for which the sediment is being eroded during the simulations. Nine locations were selected for this analysis (Figure K-1) that make use of the 28 day freshet simulation of 2014. For each location, a time series of flow relative to the critical flow velocity (determined by the Shields method) is presented (Figures K-14 to K-22). It was found that the sediments are set in motion by the tidal flow during a relatively small fraction of the simulation period (0.3% to 21.8%) when the peak tidal flow exceeds the estimated critical velocity, and do not travel far. A similar analysis is repeated for two of the locations using the high resolution MORPHO results, with similar results.

### 2.5.3 Assessment

DFO has determined that the concerns raised regarding the limited supporting information on sediment simulation have been addressed adequately. A more fulsome assessment of the regional model predictions of sediment transport, seabed erosion, and deposition has been provided by NRCan.

# 3.0 Evaluation of Model Results and Consequences

In this section, results presented in the Supplement Modelling report are examined with respect to topics of primary interest to DFO Fisheries Protection Program.

Three key topics are considered:

1. Potential for material alteration of the Flora Bank
2. Changes in Total Suspended Solids (TSS) over Flora Bank

3. Changes in the currents in the vicinity of the structures

## 3.1 Potential for material alteration of Flora Bank

### 3.1.1 SW Tower and Anchor Block

The results presented by the proponent have consistently shown that the perturbations to the natural flows with the greatest potential for material alteration of Flora Bank are associated with the two largest structures, the SW Tower and the Anchor Block. Results of the high resolution simulations are most relevant in this regard as these cases have sufficient spatial resolution to represent the dominant physical processes that are expected to occur in proximity of these large structures. The tide-only case is probably the most useful one as it likely provides the best representation of the conditions that typically prevail through most of the year. The tide+freshet case is appropriate only for times of appreciable river discharge which is limited to a period of about four weeks during spring to early summer.

The following are some of salient results of the high resolution modelling with respect to the potential for material alteration of Flora Bank.

- The high resolution simulations show that some scouring of the bottom sediment at the margin of Flora Bank is likely to occur due to the flows that develop in the lee of the structures during flood tide. This erosion leads to a slow, gradual change in the seabed at the western margin of Flora Bank.
- As discussed below, this slow gradual erosion may persist for an indefinite period of time, perhaps for many years.
- The erosion over a period of one year (based on linear extrapolation of a 28-day simulation) is of limited areal extent and relatively remote from the historical locations of eel grass beds. This is also the case for the simulation of the 50-year return period storm.
- Although the Anchor Block is larger than the SW Tower, it is evident from the results that the potential for scour on Flora Bank arises mainly from the presence of the SW Tower. This is due to the direction of ambient currents and because the SW Tower is to be situated closer to the Bank.
- In the case of the SW Tower, the 5 cm/year erosion contour extends within the 3.8 metre depth contour that is taken to delineate the edge of Flora Bank (e.g., Figures 6-30, 6-39, 6-44). The area over the Bank for which greater than 5 cm/year of sediment is eroded is about 1-2 times larger than the area of the tower and its scour protection in the tides-only case, and about three times larger in the 50-yr storm case.
- Scour protection (rip-rap) is an effective measure to mitigate scour immediately about the structures. This applies to both the construction and operation phases of the Project. It should be noted, however, the rip-rap has little influence beyond the areas that are directly protected.
- The simulations show considerably reduced erosion at the margin of Flora Bank when the obstruction presented by the SW Tower is changed from a rectangular shape to a circular one (e.g., Figures 6-43, 6-44). This would appear to be an obvious measure that could be taken to mitigate the potential impact of the SW Tower on Flora Bank. It would also be an appropriate mitigation measure to apply curved rather than rectangular temporary structures during construction as required.
- The freshet component of the tides + freshet simulation provides about a 5 cm/s current from east to west across the bank. This effectively reduces the flow over the Bank during

flood tide. As a result, there is somewhat reduced erosion of the margin of Flora Bank in the tide+freshet case relative to the tide-only case.

### 3.1.2 Trestle structures

The trestle has been represented in the regional model as a porous plate that exerts drag on the flow. The level of drag was calibrated to reduce flows and wave energy by a factor of 0.9 (i.e. blocking 10% of wave energy and current). Given that the design of the trestle pilings is such that they will block 1-2% of the area along the length of the trestle, this reduction factor is regarded as a conservative one that is likely to overestimate the effects of the trestle bents. The 50-year extreme storm simulation (Section 6.1.1; Figure 6-7) indicates that the trestle is most likely to alter the net erosion and deposition patterns along the western flank from Agnew and Flora Bank from the northwest corner of Agnew Bank to Kitson Island. In order to verify the Proponent's predictions, this area would be the most suitable for monitoring for potential long term changes in bottom morphology. Otherwise, the modelling results suggest that the impact of the trestle on Flora Bank is likely to be limited.

### 3.1.3 Remaining uncertainties

The high resolution simulations consistently show that the greatest potential for material alteration of the bank is found in immediate proximity of the SW Tower. While the duration of the simulations is insufficient to provide information on the long-term evolution of the bank in this area, the most likely scenario is for continued slow erosion at rates similar to those evident in the tide-only high-resolution simulation. The duration of this continued slow erosion is uncertain.

A discussion is given in Section 6.4 of the Supplemental Modelling Report regarding the long term evolution of the bank due to scour in proximity of the SW Tower and Anchor Block. Extensive literature on the topic of scour is cited to argue that a steady state will be achieved. The key conclusion is that while the eddies shed in the lee of the SW Tower and Anchor Block during flood tide lead to erosion beyond the scour protection, eventually an equilibrium will be reached after which scour "will slow to a relative halt when the sediment around the structure is too deep to be mobilized" [page 169]. The Proponent also asserts that "equilibrium depths around the edges of the rip-rap scour protection are likely to be reached in several months to a few years" [page 170]. First, it may be noted that the simulations show that scour is not limited to the edge of the scour protection. Near the SW Tower, the scour extends beyond the 3.8 m depth contour taken to mark the edge of Flora bank (e.g. Figures J-4 and J-56, for the tide-only and storm cases, respectively.) Second, it is worth noting that no evidence has been adduced to support the time scale of several months to a few years.

It is not possible, in fact, to determine from either the simulations presented in the Supplemental Modelling Report, nor from the cited scientific literature, the time it will take for scour to come to a halt and to achieve a state of equilibrium. Nor can any estimate be given for the final extent of scour. As emphasized in the Supplemental Modelling Report (page 169), "the rate of scour will be slow". Accordingly, the fractional change in the depth of the seabed will also vary slowly. Since scour "will slow to a relative halt when the sediment around the structure is too deep to be mobilized", it would not be unreasonable to expect that such a process will operate continuously in the vicinity of the structures for long time, perhaps even as long as the lifetime of the Project. As discussed in the next section, this may be expected to have a persistent impact on levels of total suspended solids (TSS) over the Bank.

## 3.2 Changes in Total Suspended Solids (TSS) on Flora Bank

This section examines results from high-resolution model simulations with respect to changes in total suspended solids (TSS) due to installation of the SW Tower and Anchor Block. It should be noted that while the tide-only simulation is considered to be the case that is most representative of typical conditions, many of the results discussed in Supplemental Modelling Report are drawn from the tide+freshet case. Accordingly, to evaluate changes in TSS it has been necessary to place greater reliance on the video animations of the tide-only case. The following are some of the salient results on TSS presented in the Supplement Modelling Report and the accompanying flow animations.

- The simulations show increases in TSS over the western side of Flora Bank due to the presence of the marine structures, particularly the SW Tower. These increased levels of TSS arise from the erosion and suspension of sediment due to the increased currents that develop in proximity of the structures.
- The flow animations clearly show that, during flood tide, vortices shed in the lee of the structures are effective at transporting the suspended sediment from the area around the structures onto the Bank.
- The increases in TSS can be characterized as short-lived, episodic events that occur mainly during periods of spring tides when tidal currents are strong (Appendix 1 – Technical Notes for Section 3.2). TSS levels are generally lower during neap tides when tidal currents are weak (Figure 6-35 of the Supplemental Modelling Report).
- Such episodic events also occur in the simulations without the structures, but less frequently. For example, in the tide+freshet simulation (Figure 6-35 of the Supplemental Modelling Report) without the SW Tower, there are three events in which the TSS concentration at a location east of the SW Tower exceeds 5 mg/L over 28 days. The simulation with the marine structures in place has 14 or 15 such events over a similar period, a 5-fold increase. (Here we are not counting the two large spikes in TSS that occur both with and without the marine structures and which are likely artifacts of the drying of the Bank during very low tides.)
- Examination of the tides-only video shows that the episodic increases in TSS levels on the western side of Flora Bank can be larger by a factor of 3-4 than those seen in the freshet+tide case (Appendix 1 – Technical Notes for Section 3.2)
- A pronounced east-west asymmetry is evident in Figure 6-34 of the Supplemental Modelling Report which shows the maximum instantaneous increase in TSS near the marine structure during the 28 day tide+freshet simulation. This asymmetry is likely associated with inclusion of the freshet-driven current in this simulation. While no similar figure has been provided for the more representative tide-only case, an attempt to compensate for the asymmetry leads to augmented TSS levels to the east of the SW Tower that is comparable to the factor of 3-4 mentioned above.
- In the simulations, the transport of suspended solids reaches the nearest eel grass beds which lie about 150 m to the east of the proposed location of SW Tower. The tide-only simulation suggests that the episodic increases in TSS may have values in the range of 9-30 mg/L at the location of the closest eelgrass observed in the surveys (150 m from the SW Tower).
- Sensitivity tests show that a change in shape of the SW Tower from rectangular to circular leads to reduced levels of TSS. This is directly related to the reduced erosion at the margin of the Bank induced by a circular Tower.

### 3.2.1 Remaining uncertainties

With respect to TSS, uncertainties remain with regard to four main points:

- There is uncertainty over how long the changes in TSS will persist. This is related to the question of the persistence of slow erosion about the marine structures, particularly the SW Tower. As noted in Section 3.1.3, this time scale cannot be estimated with confidence from the results presented in the Supplement Modelling Report. It is possible that somewhat elevated levels of TSS will persist for years over the western side of Flora Bank.
- There is uncertainty associated with the distance over which suspended sediment will be transported onto Flora Bank by eddies shed in the lee of the structures during flood tide. It is possible that the transport of sediment is limited by the length scale over which the vortices are dissipated. As suggested in Section 2.3.3, this scale may be underestimated in the simulations due to the coarsening of the grid resolution of the model with distance from the marine structure, which will increase the implicit numerical diffusion of the model.
- There is uncertainty regarding the duration of the episodes of elevated TSS levels. Results such as those shown in Figure 6-34 suggest that there will be short-lived, episodic ‘spikes’ in TSS on the western side of Flora Bank, occurring on flood tide during periods of stronger tidal current. It is difficult, however, to provide a more quantitative estimate from the information that is presented in the Supplemental Modelling Report. An estimate can be made by assuming that, for example, the eddies have a scale width of about 100 m and are advected at a speed of about 0.25 m/s by the background flow. Then passage of a sediment-laden eddy past a point will take about 10 minutes. Assuming several such eddies (say 8-10) during a flood tidal cycle would lead to a period of about 1.5 hours during which time TSS levels are elevated. If this occurs some 15 times during a 28 day period, then periods of elevated TSS would be present about 3% of the time. This suggests that locally elevated TSS levels will occur during a small fraction of the time, generally consistent with the spiky record of TSS in Figure 6-34.
- Finally, while it is clear from the simulation that levels of TTS are reduced considerably with a change to a circular the shape for the SW Tower, it is not possible to provide a quantitative estimate of this reduction from the results presented in the Supplemental Modelling Report.

## 3.3. Changes in currents in the vicinity of the structures

### 3.3.1 SW Tower and the SW Anchor Block

The high resolution simulations show that the structures introduce modifications to the background flow that are similar to those encountered in high Reynolds number flows about solid obstacles that extend through the water column (White 1979). Specifically, the flow is blocked upstream and accelerated in boundary layers along the sides of the structures. There is separation of these boundary layers immediately downstream of the structures. Vortices of alternating sign are shed continuously downstream in a pattern that is similar to a von Karman vortex street (White 1979).

The vortices shed downstream produce temporally and spatially varying perturbations to the otherwise fairly uniform background tidal flows over Flora Bank. The varying perturbations include regions of enhanced and reduced flow. The results show that SW Tower and SW Anchor Block can generate eddies with currents between 1.5 and 2 times the background flow that extend 50-100 m from the structures during spring (strong) tide conditions and 500 m during the extreme 50 year storm (see Appendix 1- Technical Notes for Section 3.3 for details). The enhanced currents will occur in the lee of the structures – that is downstream relative to the flow direction. During spring tides conditions this means currents of 35-45 cm/s at distances of 50-100 m from the structures. Overall, on every tidal cycle (12.4 hours), the enhanced currents last for 2-3 hours to the east of the structure and then three hours later they last for 2-3 hours to the west. The width of the enhanced current region is 1-2 times the size of the structure. The enhanced currents will extend through the water column over the bank (the water is shallow). It should also be noted that currents associated with downstream eddies will vary on relatively short time scales (e.g., 10-20 minutes) compared to the variation in tidal currents.

The Proponent states (page xxi of Executive Summary) that

*"… modelling results indicate that localized current changes and eddies in the local vicinity of the proposed SW Tower and SW Anchor block (within tens of metres of the structures) are evident, but are transient, mobile and of limited magnitude."*

This statement understates the spatial extent of the increased currents that are evident in the model results.

### 3.3.2 Trestles

The trestles are modelled as frictional elements (porous plates) in the regional model simulations (Delft-3D) and so will result in slightly weaker currents for the water passing through the trestles. Given that the trestle piles only block 1-2% of the area along the length of the trestle (page 10), they are expected to have an impact on the currents that is limited to the immediate proximity of the trestle bents.

### 3.3.3 Remaining uncertainties

As is nearly always the case, the Reynolds number of the real flows will be larger than those of the numerical simulations. Hence, in the actual flows there will invariably be greater turbulence in the wake behind the main structures than is seen in the high resolution simulations. In addition, the shedding of vortices may be more chaotic, and less periodic, than in the simulations.

As argued in Section 2.3.3, DFO expects that the eddies will propagate further onto the Bank than indicated by the simulations, and therefore the enhanced currents will extend further downstream from the two main structures. Under typical tidal conditions DFO maintains that 100-200 m would be a conservative estimate of the extent of the enhanced currents (35-45 cm/s).

## 4.0 Conclusions

Main results of this review are:

- DFO finds that the Supplemental Modelling Report (Hatch, 2015b) addresses adequately and with sufficient accuracy the concerns expressed by CEAA in its June 2, 2015 letter to the Proponent. Accordingly, DFO finds that the information provided by the Proponent is sufficient to complete a review, and that the modelling approach is adequate to evaluate the potential impacts of the Project on Flora Bank.
- The regional ocean model, based on Deflt3D is sufficient for describing the background (preconstruction) conditions, and for assessing the potential impacts of the pilings used to support the trestle.
- The high-resolution modelling results are most suitable for assessing the potential impacts of the two large marine structures: the SW Tower, and the SW Anchor Block.

Salient results of the modelling work presented in the Supplemental Modelling Report (Hatch, 2015b) are:

- The simulations show that the SW Tower and Anchor Block are the marine structures most likely to have an impact on Flora Bank. Concomitantly, the results show that the trestle pilings can be expected to have a very limited impact on Flora Bank due to their small size.
- The SW Tower is more likely to have an impact than the SW Anchor Block on Flora Bank owing to the direction of ambient currents, and because it is to be situated closer to the margin of the Bank.
- The high resolution simulations show that scouring of the bottom sediment occurs beyond the scour protection at the margin of Flora Bank, due to the flows that develop in the lee of the large structures during flood tide. This erosion can be expected to lead to a slow, gradual change in the sea bed at the western margin of Flora Bank. Such erosion is of limited areal extent and relatively distant from historical locations of the eel grass beds found on Flora Bank.
- The simulations show that erosion beyond the scour protection will lead to episodic increases in levels of total suspended solids (TSS) over Flora Bank on flood tide during periods when tidal flows are strong (spring tides).
- Results from the simulations show that the episodic increases in TSS may last for a few hours and extend hundreds of metres from the SW Tower onto the Bank. It should be noted that this result clearly varies from the assertion in the Executive Summary that ‘Hydrodynamic effects that generate erosion and deposition, or TSS changes, dissipate within tens of meters away from the structures.’ (Page xviii of the Supplemental Modelling Report, Hatch, 2015b)
- The simulations show considerably reduced scour when the obstruction presented by the SW Tower is changed from a rectangular shape to a circular one. This can be expected also to lead to reductions in TSS. There is considerable uncertainty with regard to the time scale for equilibrium to be reached and for scour to come to a relative halt.

Recommendations for Fisheries Protection Program to consider:

1. Circularly shaped marine structures are recommended as this is likely to reduce the scour at the margin of Flora Bank, and to mitigate against increased levels of TSS. Circular structures (e.g., a circular coffer dam) would also be helpful to reduce scour and TSS levels during the construction phase of the Project.
2. Monitoring of morphological changes and of TSS levels over Flora Bank is recommended. The duration of such a monitoring program is uncertain, given the uncertainty in the time scale for the equilibrium scour depth to be reached. It is conceivable that such a program could last for several years. The monitoring would occur at more frequent intervals early in the project to verify the Proponent’s model projections regarding the slow, weak rate of erosion. Subsequently, conditions could be monitored at longer intervals (e.g., annually).

# Contributors

| Contributor | Affiliation |
|---|---|
| Patrick Cummins | Author, DFO Science, Pacific Region |
| William Perrie | Author, DFO Science, Maritimes Region |
| Charles Hannah | Author, DFO Science, Pacific Region |

| Contributor | Affiliation |
|---|---|
| Diane Masson | Author, DFO Science, Pacific Region |
| Rick Thomson | Author, DFO Science, Pacific Region |
| Lesley MacDougall | Editor, DFO Science, Pacific Region |

## Approved by

Carmel Lowe,
Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada

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## Sources of Information


Chen, Changsheng, Robert C. Beardsley, Richard A. Luettich, Joannes J. Westerink, Harry Wang, Will Perrie, Qichun Xu et al. 2013. Extratropical storm inundation testbed: Intermodel comparisons in Scituate, Massachusetts. Journal of Geophysical Research: Oceans. 118(10): 5054-5073. DOI: 10.1002/jgrc.20397. (Accessed January 11, 2016)

Deltares. 2014a. Delft3D-FLOW, Simulation of Multi-Dimensional Hydrodynamic Flows and Transport Phenomena, Including Sediments. User Manual Hydro-Morphodynamics, Version: 3.15.34158. Delft, the Netherlands.

Deltares. 2014b. Delft3D-WAVE, Simulation of Short-crested Waves with SWAN, User Manual, Hydro-Morphodynamics, Version: 3.05.34160. Delft, the Netherlands.

DFO. 2015. Technical review of 3D modelling of potential effects of marine structures on site hydrodynamics and sedimentation from the construction of the Pacific Northwest liquefied natural gas terminal. DFO Can. Sci. Advis. Sec. Sci. Resp. 2015/027. (Accessed January 11, 2016)

Hatch. 2015a. 3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation. H345670-0000-12-124-0012, Rev. 0, May 5, 2015.

Hatch. 2015b. Pacific Northwest LNG Supplemental Modelling Report for 3D Modelling Update, H345670-0000-12-124-0013, Rev.0, November 10, 2015.

Kolomiets, P., Sorockin, M., Kivva, S. and M. Zheleznyak (2014). UCEWP-MOR-UN – A Numerical Simulator for Depth-Averaged Surface Water Flow, Sediment Transport and Morphodynamics in Nearshore Zone on Unstructured Grids.

Thomson, R.E., J.F.R. Gower and N.W. Bowker. 1977. Vortex streets in the wake of the Aleutian Islands. Monthly Weather Review. 105(7):873. DOI: 10.1175/1520-0493.

White, F.M. 1979. Fluid Mechanics. McGraw Hill, 701 pp.

# Appendix 1 – Technical Notes

## 2.3 Modelling of flows in proximity of large marine structures (Anchor Block and SW Tower)

### Estimating the eddy shedding time scale

Laboratory experiments show that periodic eddy shedding occurs for flow past a circular cylinder, with the period of oscillation given by $T = D / S_T U$ , where *D* is the diameter of the cylinder and $U$ the upstream flow speed. It has been found that over a very wide range of Reynolds numbers the Strouhal number, $S_T \approx 0.2$ (White, 1979, p. 279). Similar eddy shedding has been found for large-scale air flow past isolated mountains with the Reynolds number is based on an eddy viscosity, rather that the kinematic viscosity of the fluid (Thomson et al., 1977). Taking $D = 40$ m as a reasonable scale for the SW Tower, and an upstream flow speed $U = 0.20\,\mathrm{cm\,s^{-1}}$ as a representative of tidal flow speed, yields $T = 16.7$ minutes with $S_T = 0.2$. This is comparable to the roughly 20 minute period of eddy shedding seen during flood tide in the high resolution simulations.

### Estimating the length scale for eddy propagation

A length, $L$, over which eddies may be expected to dissipate can be estimated by assuming a balance of terms between the advection of vorticity and dissipation through bottom friction. The former scales as $U\Omega / L$, with $\Omega$ is a scale for the vorticity, while the dissipation of vorticity scales as $C_D U\Omega / H$ where $C_D$ is the bottom drag coefficient and $H$ is the depth. Balancing the two yields, $L = H/C_D$ . Assuming a typical value of $C_D = 0.0025$ and taking the representative depth of Flora Bank during flood tide as $H = 2.5$ m gives a length scale of $L = 1$ km

## 3.2 Changes in Total Suspended Solids (TSS) on Flora Bank

### Analysis of Figure 6-35

Figure 6-35 shows the time histories of TSS with and without marine structures at a location in the eel grass bed for the tides+freshet case. There are two large TSS peaks for both cases: one at hour 110 and one close to hour 200. We think that these events are caused by large currents just as the bank is drying. Video M-12 shows that the peak at hour 110 peak occurs as a broad flash of high TSS (lasting 10 minutes) towards the end of ebb tide just before the bank dries. This event does not occur in video M-8 which simulates the previous ebb tide which does not cause the bank to dry. It seems likely that the large peak just before hour 200 has the same cause. We assume that these two events are a function of an interaction between of the algorithm that handles how the bank dries and the TSS calculation. In the following analysis we ignore those 2 events.

### Spring Neap/Cycle

The spring/neap cycle is the natural variation in the tidal heights and currents over the lunar cycle of new moon, first quarter moon, full moon, third quarter moon (approximately 29 days). Figure 6-35 shows that the magnitude of the TSS is very sensitive to the natural variations of the tidal currents over 28 days of simulation – basically a spring/neap cycle. There are high TSS events between hours 20 and 200 and hours 320 and 520, while there is relatively little TSS activity between hours 200 and 320 and hours 520 and 672 (the end of the 28 days).

### 3.3. Changes in currents in the vicinity of the structures

The relevant simulations are the high-resolution model simulations around the SW Tower and the SW Anchor Block using the MORPHO model.

Videos M1 and M2 show currents around both the SW Tower and the SW Anchor Block for the tides only simulation. The flow around the structures generates eddies that get shed from the structure and flow away from the structures with the background currents. The peak currents very close to the structures are about twice the background values (background about 25 cm/s and the peaks about 50 cm/s). For flood tide (M2) the enhanced currents are typically 35-45 cm/s between 50-100 m from the structures and only on the lee side (downstream). The same occurs for ebb tide (video M1). The eddies (and the enhanced currents) are generated for about 2-3 hours during the peak of ebb and flood tides. Overall, every tidal cycle (12.4 hours) the enhanced currents last for 2-3 hours to the east and then 2-3 to the west. The width of the enhanced current region is 1-2 times the size of the structure. The tidal currents are smaller during the neap phase of the 29 day spring/neap cycle and so the enhanced currents will be smaller as well.

For the 50 year storm simulation the peak enhanced currents are also about twice the background values (background about 40-50 cm/s and the peaks about 90-100 cm/s), but they extend further from the structures. Currents of 80 cm/s are present 300-500m from the Tower (video M4) and currents in excess of 80 cm/s propagate out of the field of view 500 m from the SW Anchor Block (video M5).

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Centre for Science Advice
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

Telephone: (250) 756-7208
E-Mail: csap@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

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