RESONANT OSCILLATIONS IN SMALL CRAFT HARBOURS: OBSERVATIONS AND MITIGATION MODELING EXAMPLES FROM ATLANTIC CANADA

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Agitation from swells and long waves can pose serious challenges for harbours, in terms of both infrastructure design and operations. Wave gauge observations from Atlantic Canadian harbours of varying sizes were used to assess how combinations of basin dimensions and external wave forcing may lead to swell agitation, resonance, and scour problems. This paper summarizes how basin resonances were investigated with field observations, analytical methods, and then phase-resolving numerical models. The case studies illustrate how resonance mitigation may require substantial (and sometimes impractical) changes in harbour layout. Swell and scour mitigation may be more readily achieved by modifications or additions to existing structures.

Keywords: Long waves, harbour resonance, wave modeling, wave measurements, small craft harbours

INTRODUCTION

The coast of Atlantic Canada is home to many small craft harbours that are vital to the local communities and fishing industry. North Atlantic swells, and in some cases long waves, pose challenges for harbour retrofit and expansions, requiring detailed study of the agitation processes to support coastal infrastructure design and infrastructure funding allocation.

Short wave processes (wind wave and swell with period up to 25s) around coastal structures are relatively well documented and understood, which is not always the case for long waves (periods of 25s to tens of minutes), particularly at the local level within small craft harbour basins which have a complex layout (Bellotti, 2007). Small scale semi-closed harbour basins have the potential to generate natural resonant period of typically a few minutes. This may cause problematic oscillations, typically triggered by low-frequency (LF, also referred to as infragravity IG) waves propagating through the entrance combined with unique bathymetric conditions, basin geometry and potentially atmospheric forcing (Rabinovitch 2010). When the basin's natural period matches the external long wave forcing, resonant oscillations causing large amplitude wave responses may cause localized scour, particularly at the harbour entrance, in addition to impacting moored vessels and floating dock systems.

Most literature case studies of harbour oscillations (also referred to as a 'seiching') include large ports (Sakakibara, et al., 2008, López, M., et al., 2012) with fewer examples of observations at small craft harbours (Thotagamuwage, et al., 2014, Guerrini, et al., 2014). Hence, this paper presents key results and lessons learned from a few practical case studies on oscillations in small craft harbours throughout Atlantic Canada.

FIELD OBSERVATIONS

In recent years (2014 – 2018), arrays of high frequency sampling RBR wave gauges were deployed by the authors across Atlantic Canadian harbours of varying sizes and layouts to monitor the nearshore outer-harbour wave climate and its impact on the basin hydrodynamics and wave agitation. This includes the 8 sites described on Fig.1. Long wave forcings were detected at most of the studied sites, with varying degrees of harbour response.

As will be demonstrated by numerical modeling, even relatively small water level oscillations within periods of a few minutes can generate significant scour-inducing currents. As such, one of the first, easily identifiable signatures of LF wave energy may take the shape of unusually deep scour holes around the entrance, as observed at Harbour 1 (Lower Sandy Pt, NS) from bathymetric surveys (Fig.2). In this case, the scour could not be explained by tidal currents, swell or propwash action.

When long wave processes are suspected to occur, wave gauge deployment is the necessary next step to quantify the process. An example time-series of water levels inside and outside the basin at Harbour 1 is presented on Fig.3, showing the amplified LF wave signal inside the basin on top of the attenuated swell signal. To quantify long wave energy, frequency-domain analyses were conducted on the wave gauge records at all sites. The observed frequency response of each harbour for storms of various intensities is shown on Fig.4 (top 8 plots).

The sites showing the largest amount of outside LF energy (sites 1-5, 7) shared the following characteristics regarding the location of the basin entrance:

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- On the Atlantic Coast, i.e. exposed to long swell within a moderate tidal range;
- Directly updrift of beaches and/or shoals with significant wave breaking, which are generally environments associated with IG wave generation (de Bakker, et al., 2014).

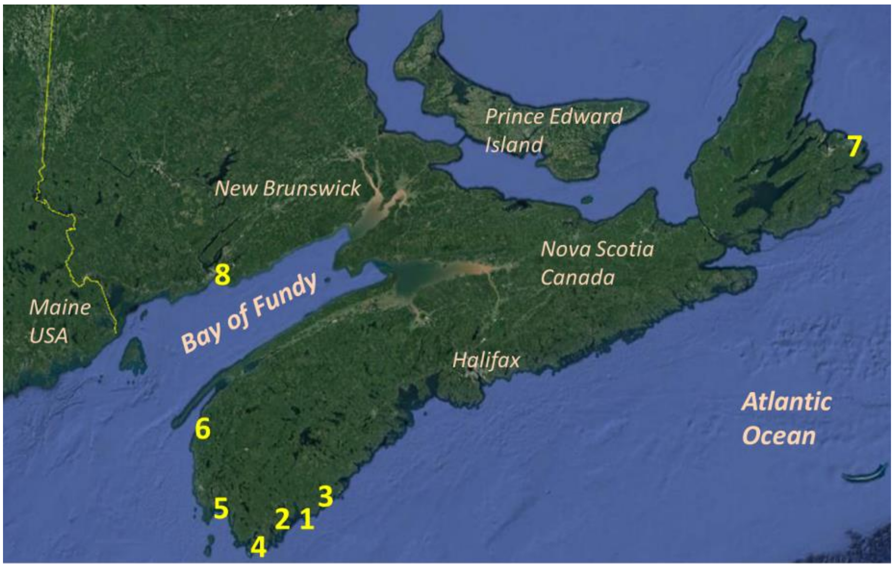

Figure 1. Study area and 8 wave gauge observation sites with instrument locations outside and inside basins. Small Craft Harbour Sites: 1.Lower Sandy Point, 2.Gunning Cove, 3.Lockeport, 4.Stoney Island, 5.Wedge Point, 6.Saulnierville, 7.Glace Bay, 8.Saint John Ferry.

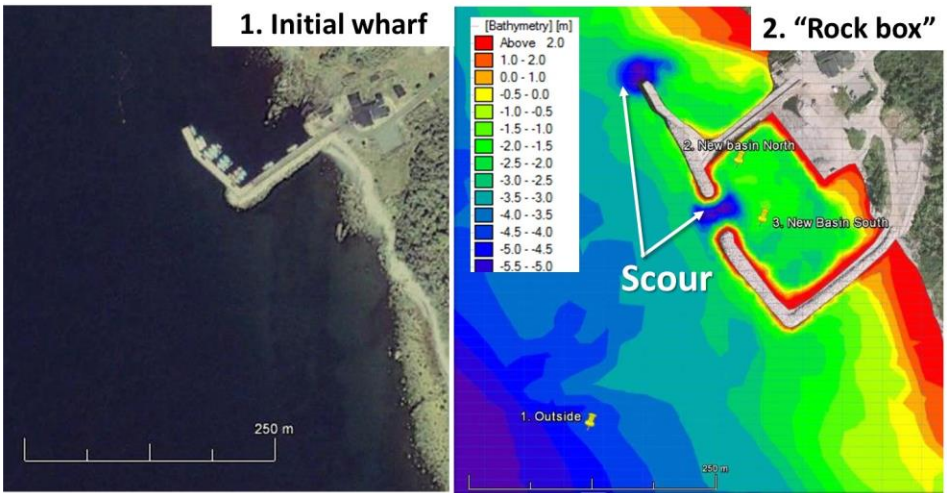

Figure 2. Harbour 1 layout and formation of long wave-induced scour holes, with three wave gauge locations

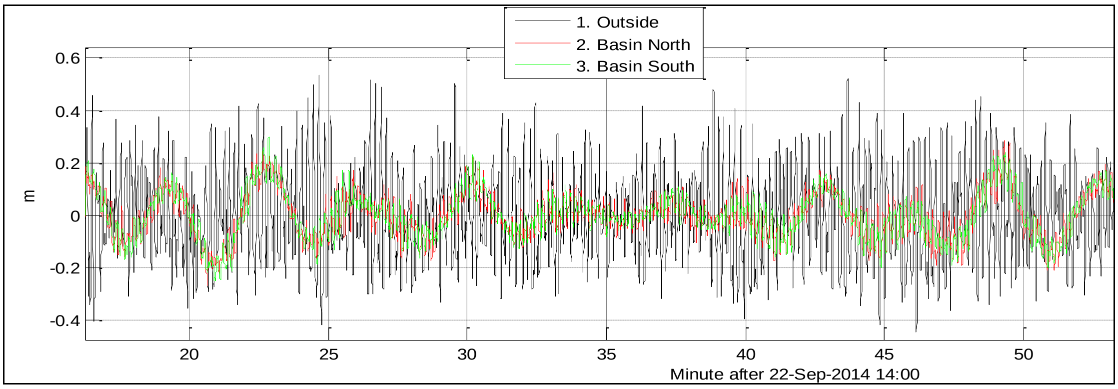

Figure 3. Sample surface elevation time-series from Harbour 1 wave gauges (1 outside, 2 inside the basin)

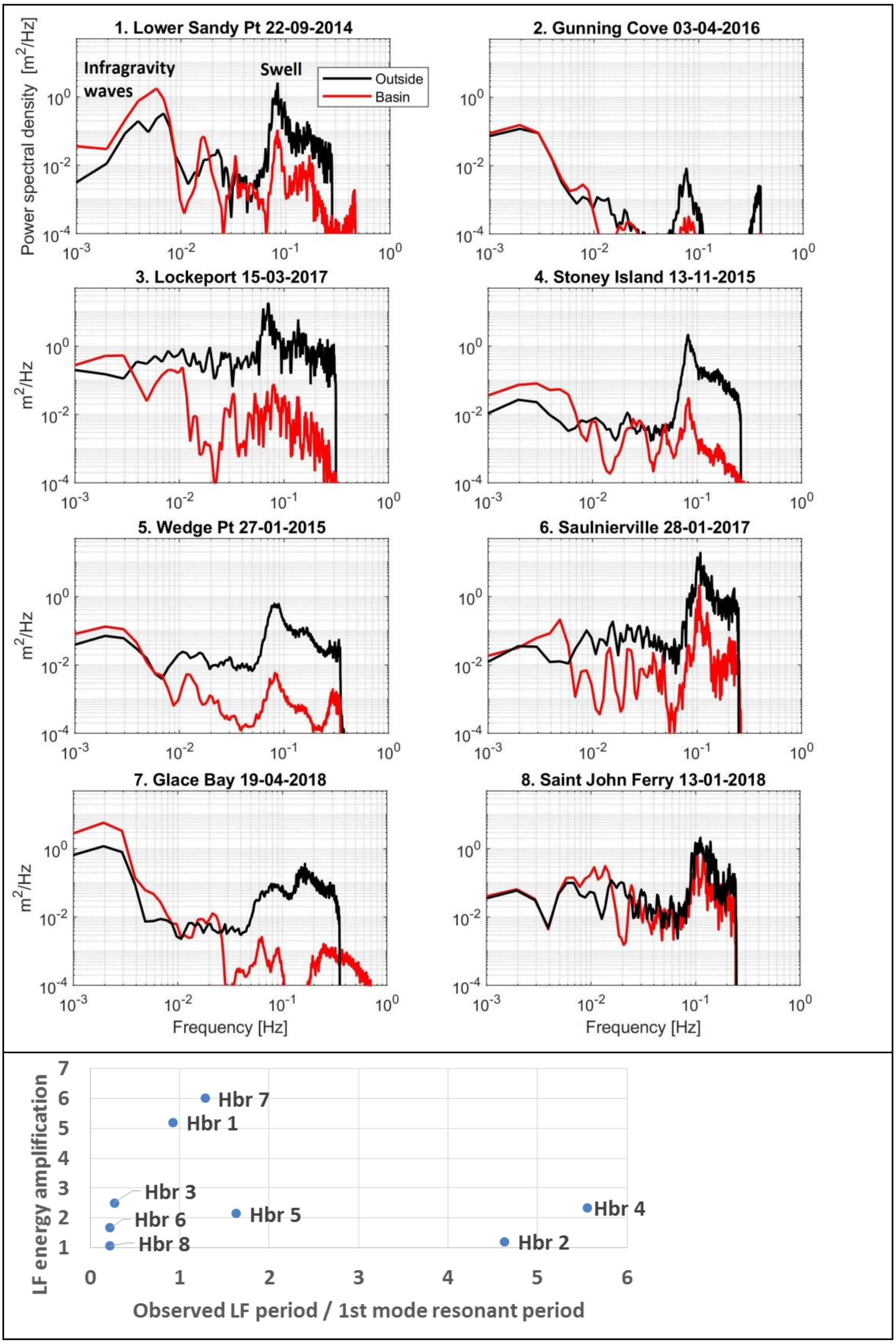

Figure 4. Top 8 plots: Frequency analysis of harbour wave gauge observations – Bottom plot: LF energy amplification vs. closeness of observed LF period to first mode resonant period estimated from analytical tools. The results show resonance is caused by incident LF wave energy coinciding with natural resonant period of the basin, particularly for Harbours 1 and 7.

ANALYTICAL FORMULATIONS FOR ESTIMATING HARBOUR RESPONSE

Natural resonant periods for each basin were first calculated by standard methodologies outlined by Sorensen et al in the USACE Coastal Engineering Manual (2012). For details, the reader is referred to the Coastal engineering Manual Fig.II-7-34 (elongated basin of Harbour 7) and II-7-31 (near-rectangular basins, used at all other sites). The observed harbour response was well correlated with natural resonant period as calculated for Harbours 1 and 7, showing severe resonant oscillations (Fig.4, bottom plot). This exercise demonstrates that the analytical formulations can be considered a valuable first step in the analysis of a harbour's potential for seiching. Wave gauge monitoring is required to confirm the hypothesis, particularly if the exposure to ocean swell is coupled with a location where large amounts of wave breaking occurs near or at the entrance.

PHASE-RESOLVING WAVE MODELING

Numerical wave modeling was conducted at Harbours 1 and 7 to further investigate the resonance process and potential mitigation measures. The field observations was used to calibrate high resolution Boussinesq wave models of the harbours, using the DHI MIKE21 BW model (Kofoed-Hansen et al., 2005).

Rectangular Basin Example (Harbour 1 – Lower Sandy Point)

As an example of such application, Fig.5 shows the modeled instantaneous sea surface elevation combining swell and LF component (left), and the strong currents (right) resulting from seemingly minor elevation differences of 0.1-0.2 m across the entrance due to resonance. At this site, the gradients in sea surface elevation during a storm are enough to drive entrance currents in the order of 1 m/s, which explains the scour holes identified in bathymetric surveys shown previously (Fig.2).

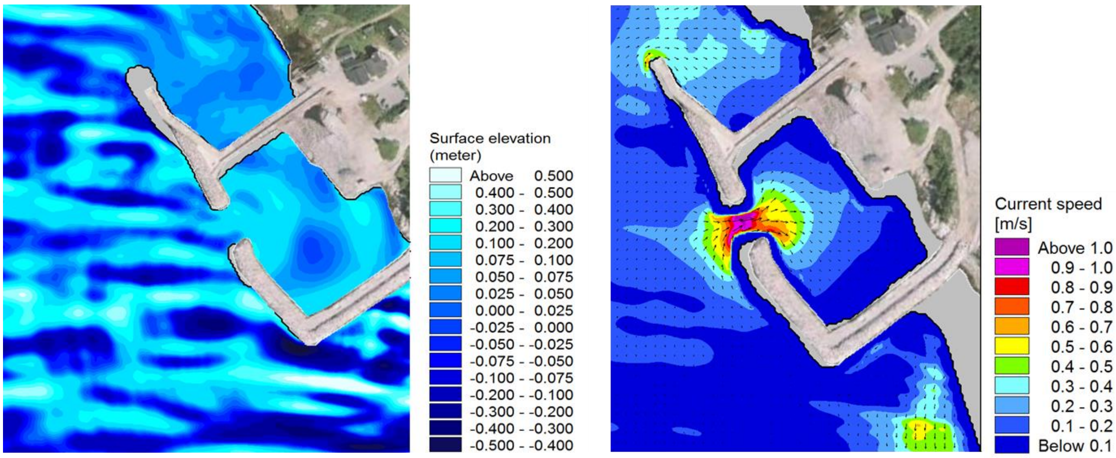

Figure 5. Sample modeled sea surface elevation (left) and long-wave induced resonance currents (right) at Harbour 1

The model was used to test various basin reconfiguration options to reduce agitation concerns, with 4 principal categories shown on Fig.6. The calculated significant wave height on the figure includes energy both from the swell and the LF component. The benefits of each option can be quantified by the model, with the following conclusions:

- A breakwater extension (Fig.6-B) can be useful to reduce swell energy, but will not reduce resonance amplitude and associated currents;
- Introducing a new limited opening in the north wharf to "leak-out" or dissipate energy (Fig.6-C) has limited effectiveness in reducing the resonance, and would introduce an additional area with strong currents;
- Only a complete reconfiguration of the existing basin (Fig.6-D) would meaningfully reduce the resonance, effectively doubling basin size by blocking the existing entrance and opening it to the sheltered north side.

At this particular site, the latter more effective solution was impractical from an operational and funding point of view, which led to the first alternative of mitigating swell energy only by means of a breakwater extension (B), and adding heavy scour protection along the entrance.

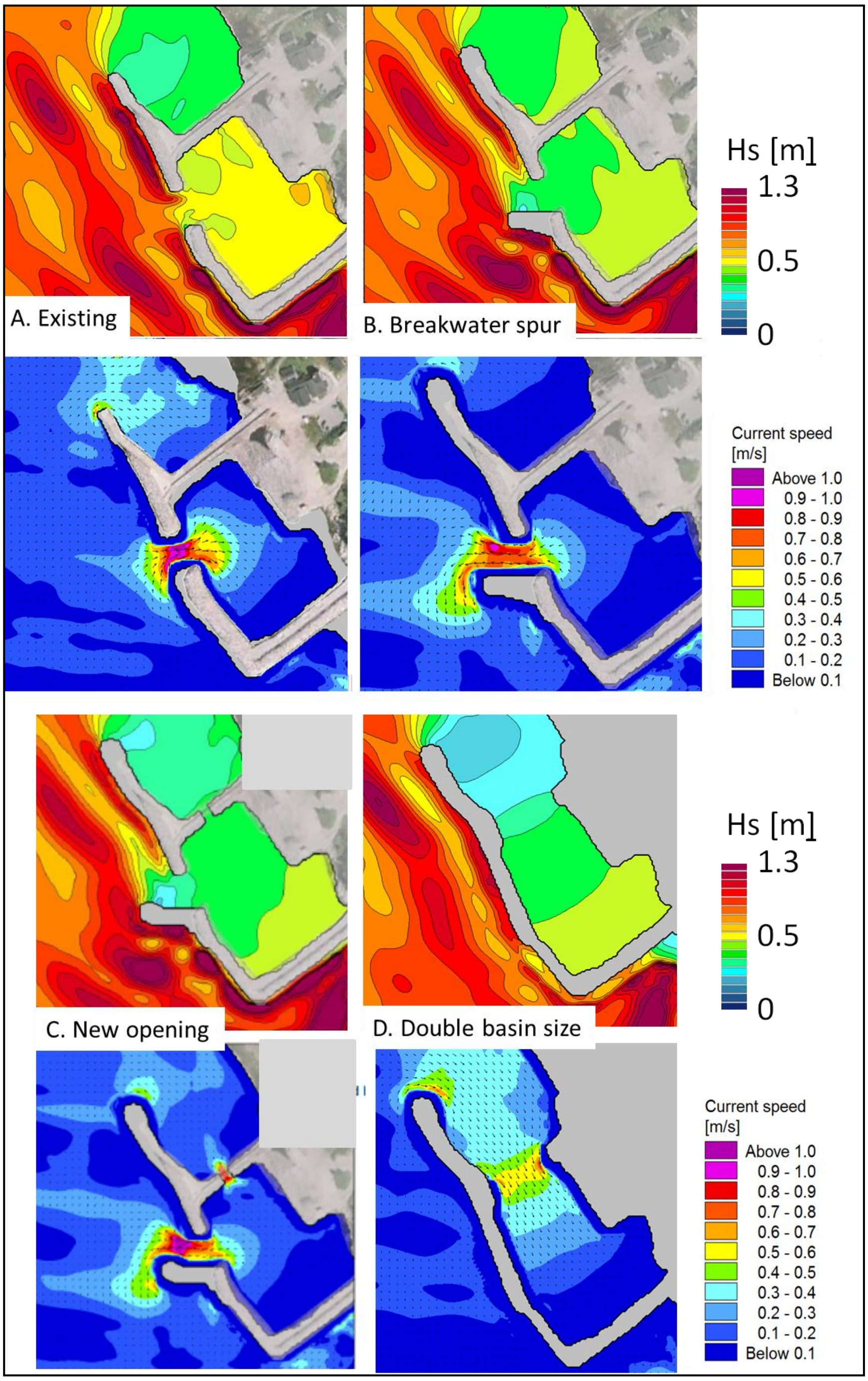

Figure 6. Sample modeled Hs (including swells + resonance) and resonance currents (right) at Harbour 1 for various basin reconfiguration options

Elongated Basin Example (Harbour 7 – Glace Bay) and White Noise Analysis

Elongated harbour basins with a low width/length ratio have a high potential to develop internal long wave basin oscillations (Dong, et al., 2013). To further investigate sensitive long wave frequencies, a white noise simulation was conducted with MIKE21 BW, following the methodology outlined by DHI's Gierlevsen et al (2001). As BW is a non-linear model, it allows for the modeling of non-linear interactions between different components of the primary wave spectrum. These interactions are known to be important for the forcing of long waves, which may lead to seiching. The white noise spectrum applied at the boundary of the model is a synthetic sea state that contains equal amounts of energy at all frequencies, to investigate the range of harbour response. The actual development of resonance would depend on the frequencies actually present in the outer sea state. Results presented in Fig.7 show natural resonant frequencies varying between 1, 4 and 8 minutes from the entrance to the inner harbour. The peak LF energy observed by the outer wave gauge was at 8 minutes, which appears to have less potential for resonance than shorter periods at 1 and/or 4 minutes. During the 2-week field program which included the event described spectrally on Fig.4, relatively less energy was observed in the 1-4 minute range from the outer wave gauge. Based on the white noise analysis, it cannot be ruled out that some events with larger amounts of 1-4 minute LF energy would generate harbour oscillations of intensity larger than observed during the field program.

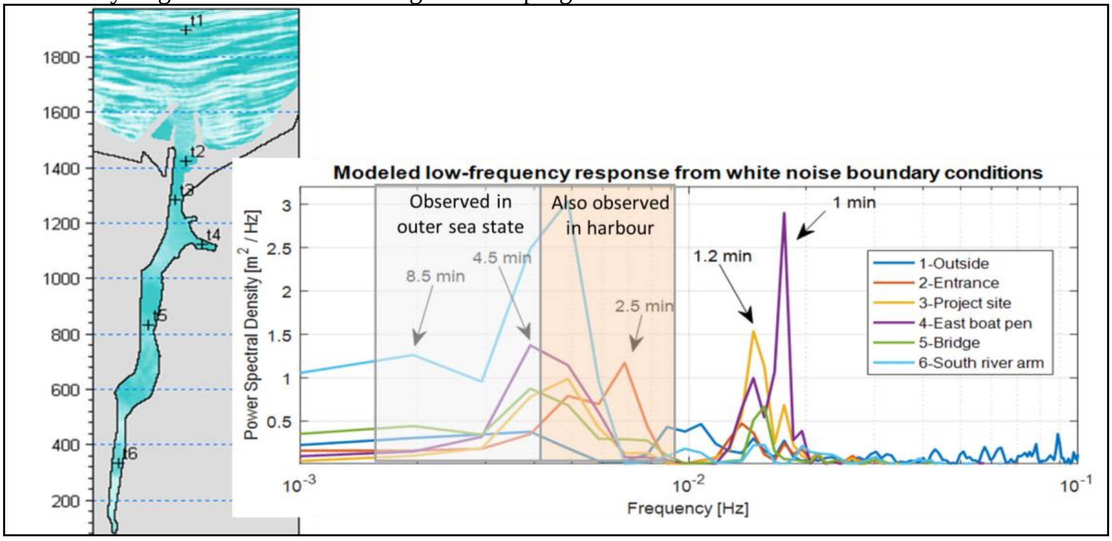

Figure 7. Results of White Noise Simulation with BW Model, Showing Natural Oscillation Frequencies

Finally, phase-resolving model results (Fig.8) again illustrate how LF sea surface oscillations can lead to strong currents, which the users of the facility confirm happen frequently, referring to the process as ‘the bore’. As with Harbour 1, it would be impractical to change basin dimensions, and modeling indicated that breakwater extensions would not be effective in reducing the LF oscillations. In this case, mooring infrastructure within the channel must be designed to operate within and withstand the strong currents.

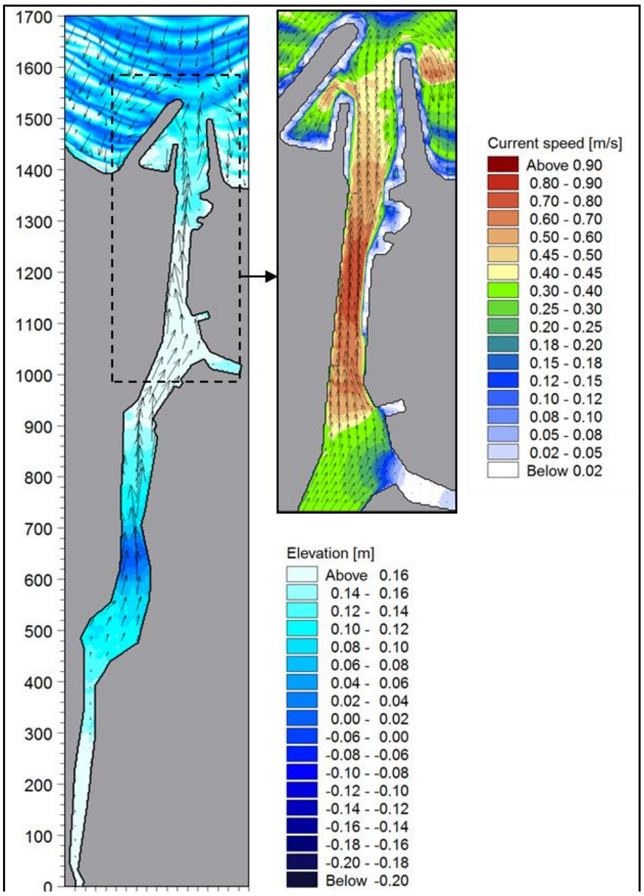

Figure 8. Phase Resolving Wave Model Snapshot (left) and Associated Currents (right)

CONCLUSIONS

Lessons learned from observations and modeling of long waves at the 8 sites described are as follows.

(1) The intensity and peak period of long wave energy is highly variable even within the relatively small geographical area of southwest and northeastern Nova Scotia. The sites showing the largest amount of outside LF energy shared the following characteristics regarding the location of the basin entrance:

- On the Atlantic Coast, i.e. exposed to long swell within a moderate tidal range;
- Directly updrift of beaches and/or shoals with significant wave breaking, which are generally environments associated with IG wave generation.

(2) Natural harbour resonance frequencies can be reasonably predicted based on basin size (Sorensen et al. 2012), then simulated more accurately with numerical modeling. Wave observations to support frequency analyses should be collected inside and outside the basin to assess the naturally occurring long wave energy in relation to the natural resonant period.

(3) In the presence of long wave processes, adequate scour protection along the harbour entrance may be critical, even for harbours with low tidal currents.

(4) Mitigating an existing resonance may require substantial rearrangement of the harbour layout in order to change the basin size. If this proves uneconomical, alternatives are reduced to reinforcing existing infrastructure such as mooring systems and scour protection, designing for strong LF currents, and further reducing swell penetration within practical limits.

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