APPENDIX 7.3-2

Woodfibre LNG – Vessel Wake Assessment

WOODFIBRE LNG – VESSEL WAKE ASSESSMENT

Introduction

Woodfibre LNG Limited (WLNG) intends to build a new LNG export terminal at Woodfibre, Howe Sound, British Columbia. WLNG has engaged Moffatt & Nichol (M&N) to perform a study of vessel wakes associated with LNG carriers calling to the new terminal at Woodfibre.

Executive Summary

The study evaluates the size of wakes potentially generated by LNG carriers when traveling through Howe Sound. Because the size of wakes increases with vessel size and speed, the largest LNG carrier anticipated at Woodfibre is evaluated in the analysis so as not to underestimate the magnitude of wakes.

The analysis shows that wakes generated by LNG carriers diminish in size with distance traveled. The largest wakes would therefore be encountered in close proximity to a vessel, whereas the wake far away from the vessel, e.g. at the shoreline might not be noticeable. The analysis also finds that vessels traveling at speeds of around 10 knots and less may not produce a noticeable wake. This is because the water is quite deep within Howe Sound. The estimated magnitude of wakes as a function of vessel speed and distance from the sailing line are summarized in Table 1.

Vessel Speed (knots)	Wave Period (s)	Wave Length (m)	Wave Height at Distance from Sailing Line (m)				
			50 m	100 m	500 m	1,000 m	1,500 m
10.0	2.7	11.3	No Significant Wake				
9.0	2.4	9.2					
8.0	2.2	7.2					
7.0	1.9	5.5					
6.0	1.6	4.1					
5.0	1.3	2.8					

Table 1 Wave period, wave length, and wave height as a function of vessel speed and distance from sailing line.

A subsequent analysis provides a brief comparison of vessel wakes and wave action produced by prevailing winds in Howe Sound. The analysis concludes that wakes generated by LNG carriers are no greater than the wind-generated waves typically encountered within Howe Sound.

Basis of Analysis

Figure 1 provides an excerpt from CHS Navigation Chart 3526, Howe Sound, British Columbia, ref.[1]. The Woodfibre LNG Terminal is circled in red. The following channels provide access to Howe Sound from the Strait of Georgia (lower part of Figure 1):

- Queen Charlotte Channel between Bowen Island and West Vancouver;
- Collingwood Channel between Bowen Island and Pasley Island;
- Barfleur Passage between Keats Island and Pasley Island.

Water depths along navigation routes within Howe Sound typically range from around 200-250 m relative to Chart Datum.

Particulars of the design vessel adopted for the analysis are summarized in Table 2. These are representative of the largest LNG carrier expected to call to the terminal.

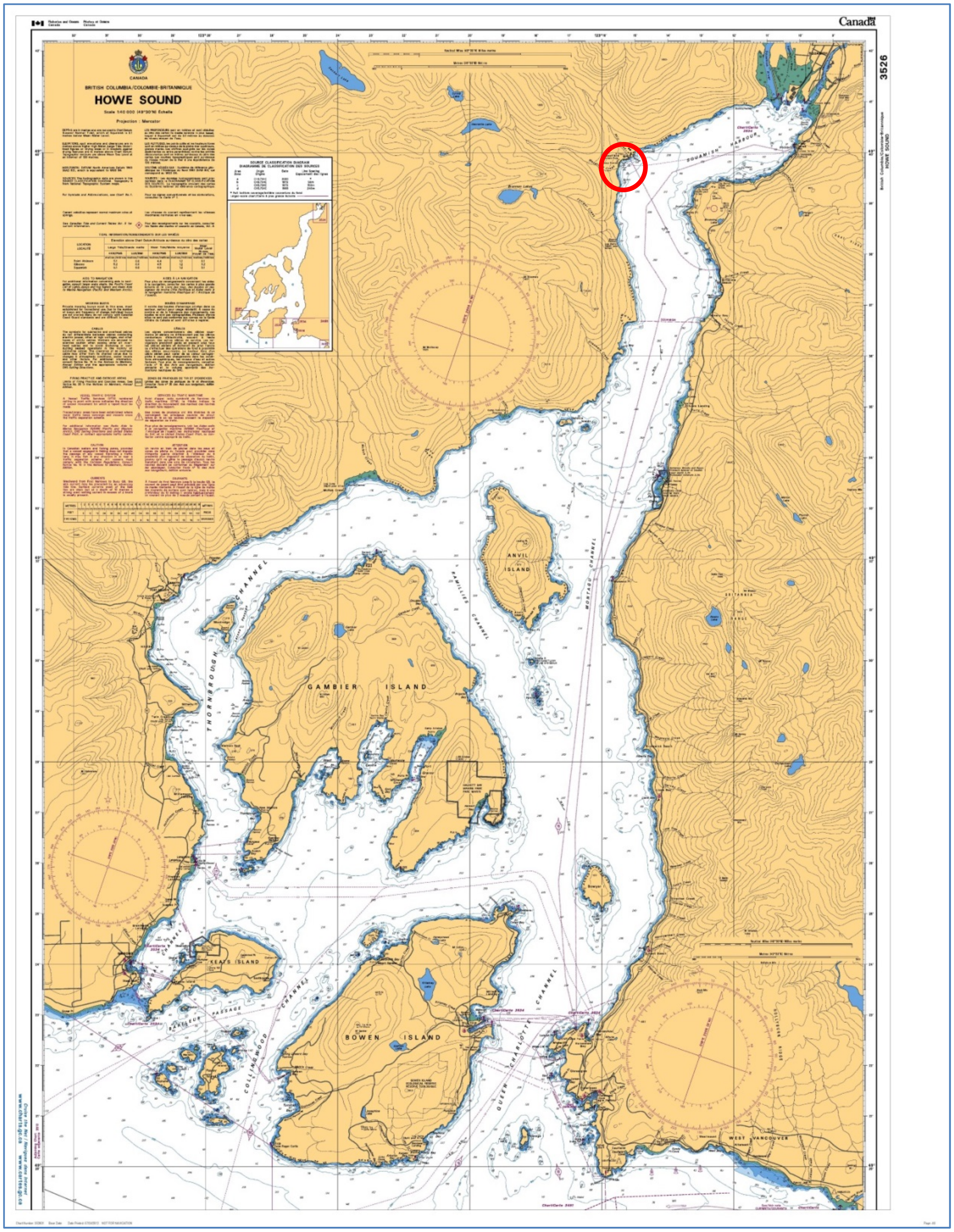


Figure 1 Howe Sound, BC, Excerpt from CHS Chart 3526. Woodfibre LNG export terminal circled in red.

Parameter	Value	Description
LOA	291.9 m	Length overall
LBP	279.6 m	Length between perpendiculars
B	46.4 m	Beam
T	11.5 m	Design draft
L_e	71.9 m	Bow entrance length

Table 2 Design vessel particulars.

Theoretical Background

A vessel in transit will produce a particular wake pattern which is outlined in Figure 2, reproduced from ref. [2].

As the vessel displaces water during its passage a varying pressure distribution develops along the hull of the vessel producing an increased pressure at the bow and stern and a pressure drop along the midsection. The associated pressure gradients produce waves that propagate out from the bow and the stern of the vessel.

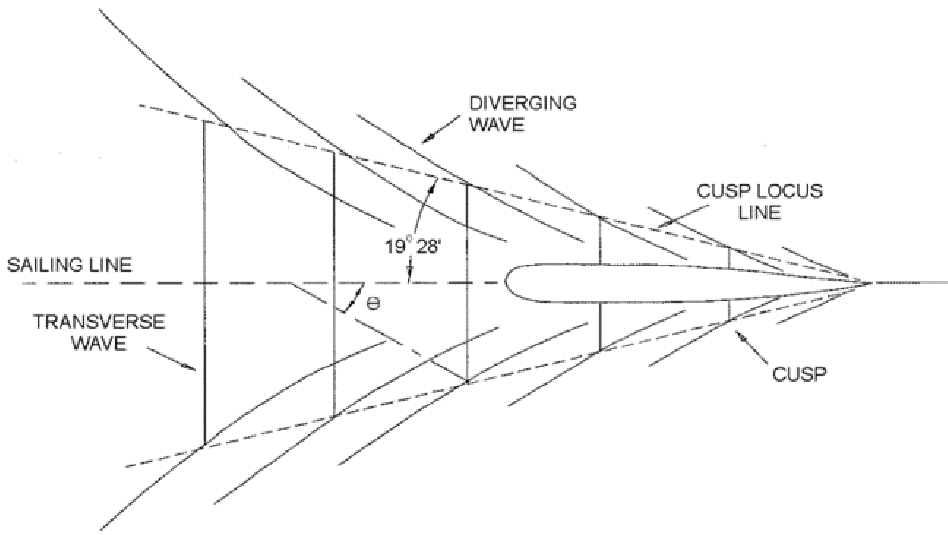


Figure 2 Vessel wake pattern.

The waves emanating from the bow (Figure 2) are commonly named bow wake and follow a diverging pattern along the path of the vessel as they propagate out from the sailing line. A series of transverse waves, stern waves, propagate along the sailing line in the direction opposite to the vessel transit.

The stern waves are typically smaller than the bow wake. The largest wave heights are encountered where the transverse waves and the diverging waves intersect, which occurs along the cusp locus line, which has been found to form an angle of 19.28° relative to the sailing line.

A detailed derivation of vessel wake is highly complex as it depends on the particular hull shape of the vessel and essentially its frictional resistance during transit. It is only with modern computational methods that solutions of the underlying equations of physics are starting to develop, although the mathematics involved is extensive and computationally very intensive. The bulk of the present research has focused on developing semi-empirical relationships to describe the overall characteristics of vessel wakes. The main parameters governing vessel wake formation have been identified to be:

- The speed of the vessel, with increasing speed yielding an increase in wave heights.
- The water depth, with decreasing water depth producing an increase in wave heights.
- The Froude Number, which relates the above parameters to the celerity of a shallow-water wave, and in the case of deep water, to the overall dimension of the vessel.
- As waves propagate out from the sailing line, the wave height attenuates with distance traveled.

Other parameters that affect wake formation, but less well understood in past research include the hull shape of the vessel, its draft, underkeel clearance, and confinement of the water body surrounding the vessel.

Several approaches have been outlined by various researchers. The approach taken in the present study is that of Verhey and Bogaerts, ref. [3], because this method specifically addresses vessel wakes in the context of wave propagation and the effect of waves along the shore, and because this method is known to produce conservative estimates of wave heights. This method is the one which has been adopted by PIANC in the guidance provided in ref. [4].

The variation of wave height with distance can be described by:

$$\frac{H_i}{h} = \alpha_1 \left(\frac{s}{h}\right)^{-1/3} F_s^{\alpha_3}$$

Where H_i is the wave height, h is the water depth, s is the distance from the sailing line and F_s is the Froude number given by:

$$F_s = \frac{V_s}{\sqrt{gh}}$$

Where V_s is the vessel speed and g is the acceleration due to gravity.

The parameter α_1 has been found to vary by vessel type and loading state. A value of $\alpha_1 = 1$ is recommended as a value for predicting the mean estimate of wave heights across a wide range of vessels. A value of $\alpha_1 = 1.2$ is recommended as an upper bound of wave height estimates. A value of $\alpha_3 = 4.0$ has been confirmed in several field studies.

Research by Verhey and Bogaerts relates α_1, the parameter which scales the magnitude of the wake relative to the vessel hull shape as: $\alpha_1 = \alpha_2\, T/L_e$, where T is the vessel draft and L_e the entrance length. The entrance length is the distance from the vessel's bow to the commencement of the parallel mid-body section and is a measure of the curvature of the bow.

LNG carriers have relatively fine lines and in the present case α_1 would then be estimated to range from α_1 = 0.24 to 0.64. This is based on ref. [3] estimates of α_2 ranging from 1.5 to 4.0.

While the methodology used herein adopts a conservative approach in order to arrive at conservative estimates of wave heights, the wakes produced by LNG carriers may be 50-80% lower than the developed estimates.

Additional characteristics proportions of the wake characteristics can be determined as follows per ref. [2]. The speed of wake propagation (celerity) is given by:

$$C = V_s\, cos(\theta)$$

Where C is the celerity, V_s is the vessel speed, and θ is the angle of wave propagation with respect to the sailing line as defined in Figure 2. The angle of wave propagation has been found to be related to the Froude Number as follows:

$$\theta = 35.27°\left(1 - e^{12(F-1)}\right)$$

Where F is the Froude Number and e is the exponential function.

The wave length is determined from the dispersion relation given by:

$$C^2 = \frac{gL}{2\pi} \tanh\left(\frac{2\pi h}{L}\right)$$

Where C is the celerity, h is the water depth, L is the wave length, and g the acceleration due to gravity.

The wave period, T, can be resolved from:

$$T = \frac{L}{C}$$

In deep water where the propagation of waves are unaffected by the bottom topography, as is the case for vessel wake propagation within Howe Sound, the wave length and wave period terms reduce to:

$$L = \frac{2\pi}{g}C^2$$

And

$$T = \frac{2\pi}{g}C$$

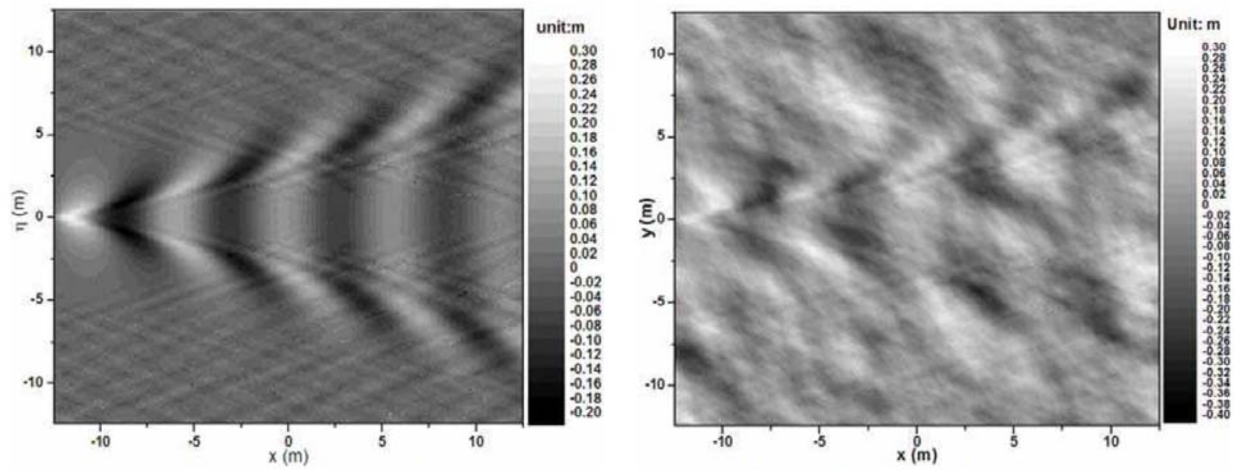
Findings

Based on the water depths in Howe Sound, Figure 1, and the design vessel particulars (Table 2), estimates of wave periods, wave lengths and wake heights as a function of vessel speed and distance from the sailing line are summarized in Table 2. The wave heights reported are representative of the height measured from the trough to the wave crest. Wave heights smaller than 0.1 m are considered insignificant.

Vessel Speed (knots)	Wave Period (s)	Wave Length (m)	Wave Height at Distance from Sailing Line (m)				
			50 m	100 m	500 m	1,000 m	1,500 m
22.0	5.9	54.7	1.46	1.16	0.68	0.54	0.47
21.0	5.7	49.8	1.21	0.96	0.56	0.45	0.39
20.0	5.4	45.2	1.00	0.79	0.46	0.37	0.32
19.0	5.1	40.8	0.81	0.64	0.38	0.30	0.26
18.0	4.8	36.6	0.65	0.52	0.30	0.24	0.21
17.0	4.6	32.7	0.52	0.41	0.24	0.19	0.17
16.0	4.3	28.9	0.41	0.32	0.19	0.15	0.13
15.0	4.0	25.4	0.32	0.25	0.15	0.12	0.10
14.0	3.8	22.2	0.24	0.19	0.11		
13.0	3.5	19.1	0.18	0.14			
12.0	3.2	16.3	0.13	0.10			
11.0	3.0	13.7					
10.0	2.7	11.3					
9.0	2.4	9.2					
8.0	2.2	7.2			No Significant Wake		
7.0	1.9	5.5					
6.0	1.6	4.1					
5.0	1.3	2.8					

Table 3 Wave period, wave length, and wave height as a function of vessel speed.

Wave heights summarized in Table 3 are representative of the vessel wake only and do not include any effects from the natural sea state present within the sound. For the portion of the smaller wave heights, these are likely to be indiscernible when dispersing under the influence of the typical wave climate within the sound. Figure 3 provides an example of vessel wake propagating on a calm water surface compared to wake combined with a typical sea state, in this case a wind speed of 11 km/h.



(a) Single ship wake (b) Ship wake on the sea surface

Figure 3 Example wake formation on calm water (a) compared with wake on sea surface (b).

Analysis of wind data obtained by Environment Canada at Pam Rock, south of Anvil Island for a typical year (2013), reveals that average wind speeds range from 12-15 km/h over the summer months, increasing to 18-22 km/h on average in the winter months. Peak annual wind speeds can reach 70-80 km/h. Mild winds tend to blow from southerly directions, while stronger winds tend to have a north-northeasterly heading. The typical over-water distances within the sound range from 13-18 km. During episodes of mild winds, wave heights typically range from 0.3-0.5 m, increasing to 1.0 to 2.5 m when stronger winds blow from north-northeasterly directions.

References

[1] *Howe Sound.* CHS Chart 3526. Canadian Hydrographic Service. Government of Canada, Fisheries and Oceans Canada. Scale 1:40,000. Projection: Mercator. Horizontal Datum: North American Datum 1983 (NAD 83). Depths in meters reduced to Chart Datum (Lowest Normal Tide). Elevations in meters above Higher High Water, Large Tide.

[2] *Coastal Engineering Manual.* Engineer Manual EM 1110-2-1100 (Part II), Chapter 7 Harbor Hydrodynamics. U.S. Army Corps of Engineers, 1 June 2006 (Change 1).

[3] *Ship waves and the stability of armour layers protecting slopes.* H.J. Verhey and M.P. Bogaerts. Delft Publication number 428. Delft Hydraulics, November 1989.

[4] *Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways.* PIANC, Permanent International Association of Navigation Congresses. Report of Working Group 4 of the Permanent Technical Committee I. Supplement to Bulletin N° 57 (1897). General Secretariat of PIANC, Résidence Palace, rue de la Loi 155, B. 9, 1040 Brussels (Belgium).