Bow and Stern Sinkage Coefficients for Cargo Ships in Shallow Open Water

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Abstract

In this paper, we develop sinkage coefficients for ships in shallow open water, or harbour approach channels with minimal transverse restriction. These sinkage coefficients may be used for under-keel clearance management by ports, pilots, and deck officers. The coefficients are calculated using slender-body shallow-water theory applied to 12 published hull forms. Results are condensed into sinkage coefficient ranges for container ships, oil tankers, bulk carriers, and membrane LNG carriers. Limitations on use of the coefficients are suggested, based on ship and navigation channel dimensions. Examples are given for container ships, bulk carriers, and LNG carriers in Australian ports.

Keywords: Sinkage; Approach channel; Shallow water; Ship hulls; Ship under-keel clearance

1. Introduction

When a ship is under way in shallow calm water, it experiences a downward sinkage and dynamic trim change, which are collectively called “squat”. This is a Bernoulli effect, whereby the free surface drops as water is accelerated along the sides of the ship. The ship then sinks hydrostatically into its own wave trough, bringing it closer to the seabed. Squat has been a significant contributing factor in several grounding incidents (Nautical Institute, 2015).

The recent PIANC guidelines for harbour approach channels (Permanent International Association of Navigation Congresses (PIANC), 2014) contain information on suitable squat allowances for different types of ships and channels. The methods are semi-empirical, and several (Hooft, 1974; Huuska, 1976; ICORELS, 1980; Millward, 1992) are based on the slender-body analysis of Tuck (1966) for ships in shallow open water. According to that theory, the midship, bow, and stern sinkage may be written

$$S_{mid} = C_{s\_mid} \frac{\nabla}{L_{PP}^{2}} \frac{F_h^{2}}{\sqrt{1-F_h^{2}}} \tag{1}$$

$$S_{bow} = C_{s\_bow} \frac{\nabla}{L_{PP}^{2}} \frac{F_h^{2}}{\sqrt{1-F_h^{2}}} \tag{2}$$

$$S_{stern} = C_{s\_stern} \frac{\nabla}{L_{PP}^{\;2}} \frac{F_h^{\;2}}{\sqrt{1-F_h^{\;2}}} \tag{3}$$

where F_h is the depth-based Froude number:

$$F_h = \frac{U}{\sqrt{gh}} \tag{4}$$

Here U is the ship speed, h is the water depth, and g is the gravitational acceleration. ∇ is the ship's displaced volume and L_{PP} is the ship's length between perpendiculars.

In open water, the sinkage coefficients C_{s_mid}, C_{s_bow}, and C_{s_stern} are predicted to be constant for each ship, irrespective of the ship speed or water depth. The sinkage coefficients should also be independent of scale. For a rigid hull, as is normally assumed,

$$C_{s\_mid} = \frac{(C_{s\_bow} + C_{s\_stern})}{2} \tag{5}$$

Equations (1), (2), and (3) suggest a semi-empirical method to predict ship sinkage. That is, perform model testing to calculate the sinkage coefficients experimentally, then apply these same empirical coefficients to predict sinkage for full-scale ships.

A problem with the semi-empirical approach is that model tests are necessarily performed in a finite-width tank, for which the sinkage coefficients are not constant, but also depend on the tank width, water depth, and ship speed. The linear finite-width theory of Tuck (1967) suggests that sinkage will increase as the channel width decreases. In addition, nonlinear effects become increasingly important as the channel width decreases. These effects mean that sinkage coefficients are found not to be constant for each ship. As an example, the MEGA-JUMBO container ship model (Uliczka et al., 2004) was found to have midship sinkage coefficients ranging from 1.40 - 1.76 in the widest channel configuration tested, and 2.02 - 2.20 in the narrowest channel configuration tested (Gourlay et al., 2015a).

Why not use smaller-scale models in shallow-water model tests, to minimize the tank width effect? This approach was taken by Graff et al. (1964) who used 6m models for deep-water tests and 3m models for shallow-water tests. Unfortunately, using small models increases the viscous scale effect, which is important for dynamic trim. Therefore choosing the model scale is a compromise between minimizing tank width effect and minimizing scale effect. Needless to say, wide tanks, such as the 10m-wide Duisburg tank, are highly sought-after for shallow-water tests.

Some authors have tried to capture the dependence on channel width through empirical corrections to the sinkage coefficients (PIANC, 2014). While this might work well for the ship models and channels used to develop the correction, the physics might not be adequately captured to be able to apply these methods to a wide range of ships.

We would recommend that complete numerical simulations be performed for ships in channels. For moderate-width channels, the linear slender-body theory of Tuck (1967) may be used; for narrow channels, the nonlinear Rankine-source method (e.g. von Graefe, 2014) may be used; for very narrow channels, the nonlinear hydraulic theory of Gourlay (1999) may be used. RANS methods are also becoming increasingly common for modelling ship sinkage and trim, especially in confined waterways (Mucha et al., 2014).

Here, we concentrate on waterways with minimal transverse restriction, such as open waterways or dredged channels, which are common for port approach channels on the Australian continental shelf. For these types of waterways, we develop sinkage coefficients that may be used for under-keel clearance management. The coefficients are calculated using the slender-body theory of Tuck (1966) for open water; Tuck (1967) for canals; and Beck et al. (1975) for dredged channels. The methods are implemented in the computer code “ShallowFlow” developed at the Centre for Marine Science and Technology, Curtin University (Gourlay, 2014). For wide channels, slender-body theory has been shown to give good results for container ships at model scale (Gourlay et al., 2015a), container ships at full scale (Gourlay, 2008a), bulk carriers and tankers at model scale (Gourlay, 2006; Gourlay et al., 2016), and bulk carriers and tankers at full scale (Gourlay, 2008b; Ha et al., 2016).

2. Cargo ship types and representative ship models

While lines plans for merchant cargo ships are generally confidential, many ship hull forms for research objectives have been developed over the years. Here, 12 published representative ship models have been chosen for analysis. These fall into the categories of container ships, bulk carriers, oil tankers, or membrane LNG carriers. Oil tankers and bulk carriers are grouped together due to parallels in hull shape between them.

Ships carrying different types of cargo have evolved to have different hull shapes. Shipping containers are fairly low density and need to be transported quickly, so container ships tend to have low block coefficient, to maximize waterplane area for their displacement and give an efficient hull shape. Bulk carriers and tankers have high-density cargo with less requirement for speed, so the hull shapes tend to have high block coefficient, to maximize deadweight capacity at the expense of hull efficiency. Membrane LNG carriers are generally in between container ships and tankers in terms of hull shape and block coefficient, but have shallower draught because of their low-density cargo.

In this paper, we shall be focussing only on container ships, bulk carriers, oil tankers, and membrane LNG carriers, which are the hull types we shall be analysing. Therefore, these results are not directly applicable to other cargo ship types, such as Ro-Ro vessels, car carriers, livestock carriers, Moss LNG carriers, LPG carriers, and warships.

The container ships modelled are:

- "Duisburg Test Case" ("DTC", 355m L_{PP}), designed by the University of Duisburg-Essen, Germany in 2012, representative of a 14,000 TEU Post-Panamax container ship (El Moctar et al., 2012)

- "KRISO Container Ship" ("KCS", 230m L_{PP}), designed by Korean Research Institute Ships and Ocean Engineering (KRISO) in 1997, representative of a 3,600 TEU Panamax container ship (Lee et al., 2003)

- "JUMBO" (320m L_{PP}), designed by SVA Potsdam, Germany in 1995, representative of a 5,500 TEU Post-Panamax container ship (Uliczka et al., 2004)

- "MEGA-JUMBO" (360m L_{PP}), designed by VWS Berlin, Germany in 2001, the design ship for the Jade Weser port in Germany, representative of a 12,000 TEU Post-Panamax container ship (Uliczka et al., 2004)

- "FHR Ship D" (289.69m L_{PP}), designed by Flanders Hydraulics Research and Ghent University, Belgium in 1996-2000, representative of a Post-Panamax container ship (Gourlay et al., 2015b; Vantorre and Journée, 2003)

- "FHR Ship F" (190m L_{PP}), designed by Flanders Hydraulics Research and Ghent University, Belgium in 1996-2000, representative of a Panamax container ship (Gourlay et al., 2015b; Vantorre and Journée, 2003)

The oil tankers modelled are:

- "KRISO Very Large Crude Oil Carrier" ("KVLCC", 320m L_{PP}), designed by Korean Research Institute Ships and Ocean Engineering (KRISO) in 1997, representative of a 300,000 DWT oil tanker (Larsson et al., 2003; Van et al., 1998)

- "KRISO Very Large Crude Oil Carrier 2" ("KVLCC2", 320m L_{PP}), designed by Korean Research Institute Ships and Ocean Engineering (KRISO) in 1997, representative of a 300,000 DWT oil tanker, the second version of the KVLCC with more U-shaped stern frame-lines (Larsson et al., 2003; Van et al., 1998)

The bulk carriers modelled are:

- "Japan 1704B standard series" (6m model L_{PP}), designed by National Maritime Research Institute (NMRI, former Ship Research Institute of Japan), representative of a Panamax bulk carrier (Yokoo, 1966)

- "Japan Bulk Carrier" ("JBC", 280m L_{PP}), designed by National Maritime Research Institute (NMRI, former Ship Research Institute of Japan), Yokohama National University, and Ship Building Research Centre of Japan, representative of a Post-Panamax bulk carrier (NMRI, 2015)

- "FHR Ship G" (180m L_{PP}), designed by Flanders Hydraulics Research and Ghent University, Belgium in 1996-2000, representative of a Panamax bulk carrier (Gourlay et al., 2015b; Vantorre and Journée, 2003)

The membrane LNG carrier modelled is:

- "KRISO Liquefied Natural Gas Carrier" ("KLNG", 266m L_{PP}), designed by Korean Research Institute Ships and Ocean Engineering (KRISO) in 2003, representative of a 138,000 m^3 membrane LNG carrier (Van et al., 2003, 2006)

In this paper, hull shapes of the above 12 ships have been developed from supplied IGES files and the published lines plans using Rhino, AutoCAD, and Maxsurf Modeler. Calculated details of the modelled vessels are given in Table 1 and Table 2. Note that some of the particulars have been calculated from the modelled vessels and are approximate. Longitudinal centre of buoyancy (LCB) and longitudinal centre of floatation (LCF) are given as % of L_{PP} forward of aft perpendicular (AP). Block coefficient is the ratio of displacement to (L_{PP}.Beam.Draught). Dimensions of the Japan 1704B are at model scale, as no full-scale dimensions were specified.

Table 1.
Details of the container ships used for numerical calculations.

Particulars	Container ships					
	DTC	KCS	JUMBO	MEGA-JUMBO	FHR Ship D	FHR Ship F
L_{PP} (m)	355.00	230.00	320.00	360.00	291.13	190.00
Beam (m)	51.00	32.20	40.00	55.00	40.25	32.00
Draught (m)	14.50	10.80	14.50	16.00	15.00	11.60
Block coefficient (-)	0.660	0.650	0.721	0.681	0.604	0.600
Displacement (m^3)	173,337	52,013	133,901	215,775	106,226	42,338
Max. section area (m^2)	730.02	342.42	564.22	867.53	593.13	365.02
LCB (%)	49.04	48.52	49.30	49.97	47.05	47.74
LCF (%)	45.38	44.33	45.84	49.12	44.54	45.43

Table 2.
Details of the oil tankers, bulk carriers, and LNG carrier used for numerical calculations.

Particulars	Oil tankers		Bulk carriers			LNG carrier
	KVLCC1	KVLCC2	Japan 1704B	JBC	FHR Ship G	KLNG
L_{PP} (m)	320.00	320.00	6.00	280.00	180.00	266.00
Beam (m)	58.00	58.00	0.923	45.00	33.00	42.60
Draught (m)	20.80	20.80	0.334	16.50	11.60	11.30
Block coefficient (-)	0.810	0.810	0.801	0.858	0.839	0.749
Displacement (m^3)	312,738	312,622	1.482	178,370	57,806	95,940
Max. section area (m^2)	1,203.80	1,203.80	0.306	741.11	381.69	473.53
LCB (%)	53.48	53.52	54.93	52.53	53.36	49.97
LCF (%)	49.75	50.02	52.16	49.30	51.09	47.65

We can see that there are significant differences in hydrostatic characteristics between the hulls. Block coefficient ranges between 0.60 and 0.72 for the container ships, 0.80 and 0.86 for the oil tankers/bulk carriers, and 0.75 for the LNG carrier. Longitudinal centre of buoyancy (LCB) ranges from 47.05% to 49.97% for the container ships; from 52.53% to 54.93% for the oil tankers/bulk carriers; and 49.97% for the LNG carrier. Longitudinal centre of floatation (LCF) is aft of the LCB by on average 2.8%, 3.0%, and 2.3% of L_{PP} for the container ships, oil tankers/bulk carriers, and LNG carrier respectively. By looking at these, we see that each ship hull exhibits typical features of their ship type. Slower full-form ships such as tankers or bulk carriers, for example, tend to have their LCB well forward of amidships, while fine-form ships such as container ships and LNG carriers have their LCB slightly aft of amidships (PIANC, 2014).

Comparative body plans of the ships are shown in Fig. 1 - Fig. 4. These body plans illustrate 50 evenly-spaced stations from the transom to the front of the bulb. The body plan of the Japan 1704B has a different scale to the others.

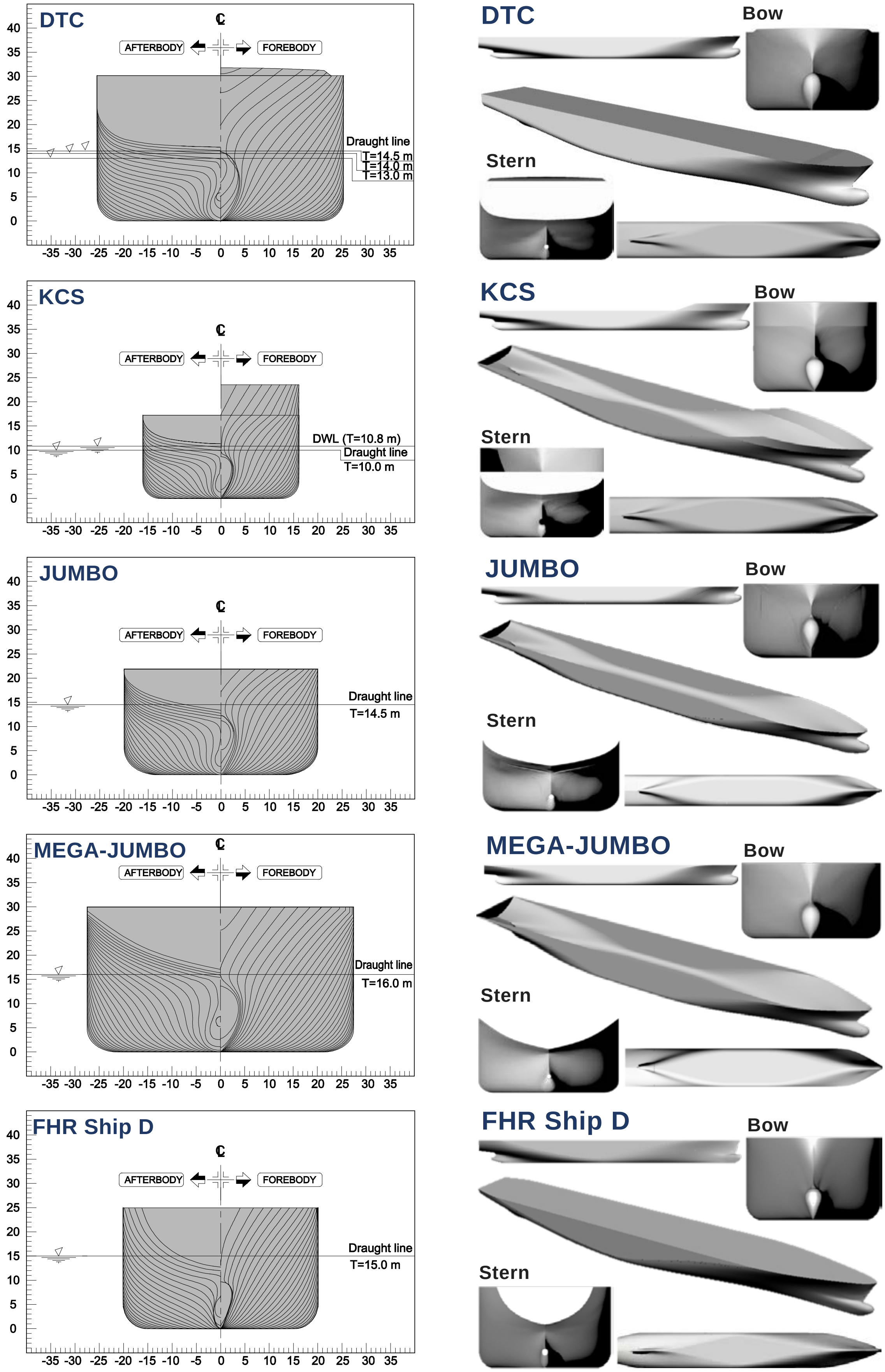
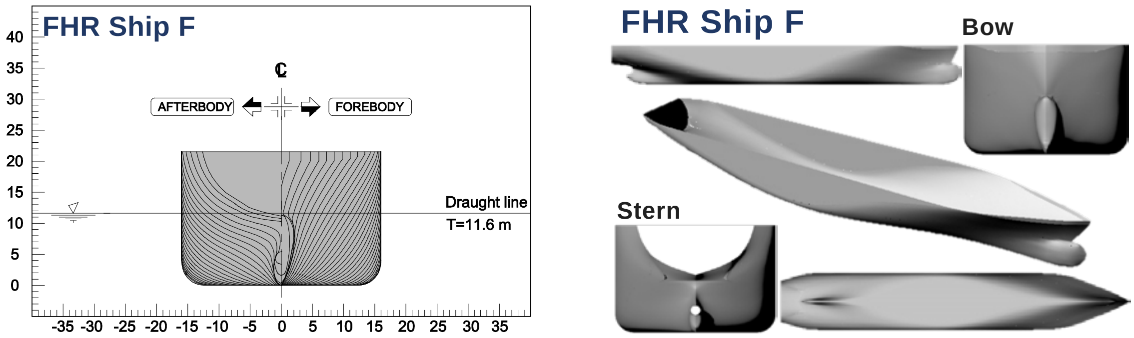


Fig. 1. Body plans and rendered views of the container ships.



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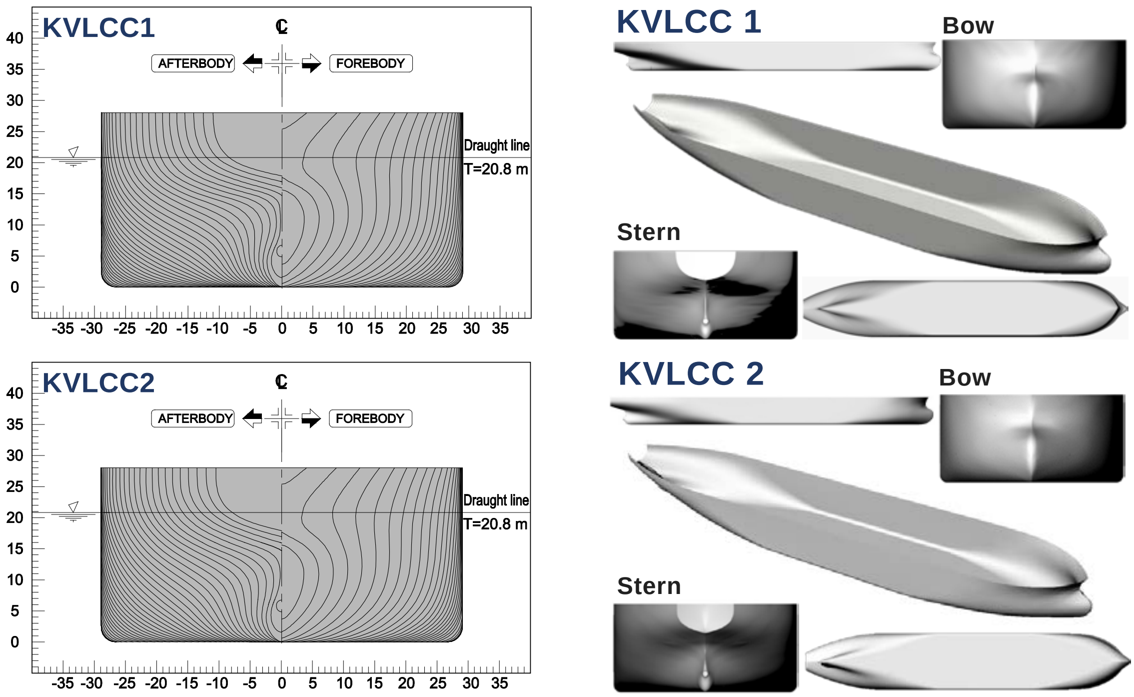

Fig. 2. Body plans and rendered views of the oil tankers.

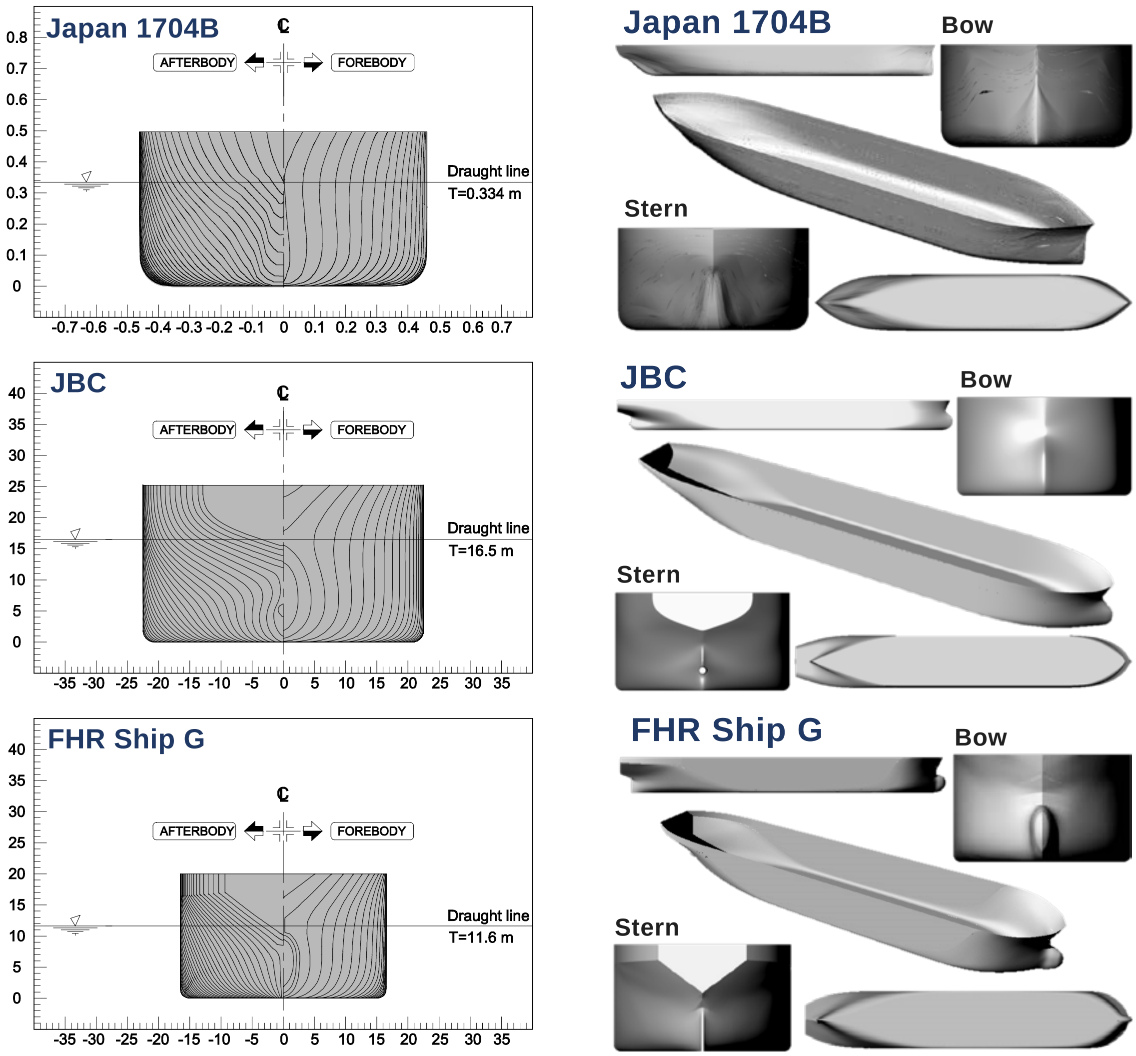

Fig. 3. Body plans and rendered views of the bulk carriers.

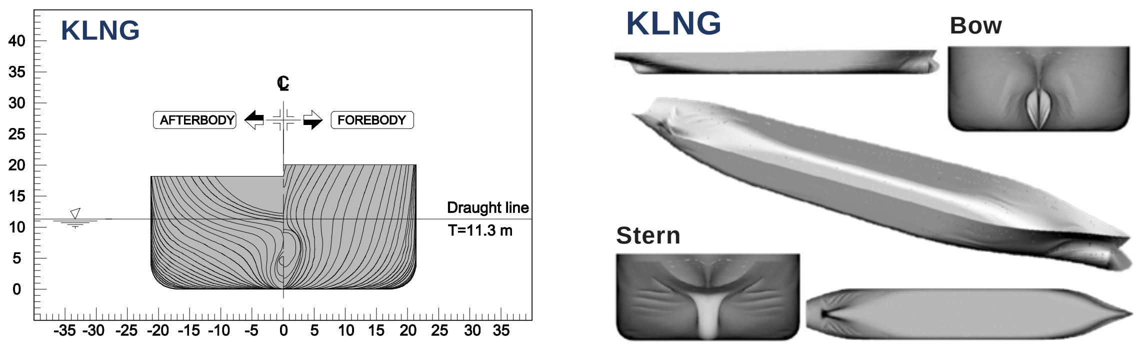

Fig. 4. Body plan and rendered views of the LNG carrier.

We can see that there are significant differences in hull shape between the different ship types. Distinctive characteristics in hull shape for the container ships are: a pronounced bow bulb; a wide and nearly flat-bottomed transom stern; and aft sections that are close to horizontal at the waterline. For the oil tankers and bulk carriers, the forward sections are almost vertical, and aft sections are not far from vertical, at the waterline. The oil tankers and bulk carriers have smaller transoms and sharper bow bulbs than the container ships. The KLNG is generally in between the container ships and the oil tankers with regard to hull shape.

In addition, Fig. 1 - Fig. 4 show the bow, stern, profile, bottom, and perspective views of the modelled ships, emphasizing each ship type's features in hull shape. We see that the container ship hulls have streamlined forward and aft sections, whereas the hulls of the oil tankers and bulk carriers are very-block with a long parallel midbody. The KLNG hull has a long parallel midbody and streamlined forward and aft sections.

3. Open-water sinkage coefficients

We shall now calculate open-water sinkage coefficients for all of the hulls using the slender-body theory of Tuck (1966). The theoretical sinkage coefficient for each ship type, as calculated using equation (1), (2), and (3), is shown in Table 3.

Table 3.
Calculated bow, stern, and midship sinkage coefficients for open water.

Ship Hulls		Draught (m)	Sinkage Coefficient (C_s)			Trim (+, stern down)
			Bow (C_{s_bow})	Midship (C_{s_mid})	Stern (C_{s_stern})	
Container Ships	DTC	13.0	1.460	1.342	1.245	(-)
		14.0	1.590	1.272	1.010	(-)
		14.5	1.647	1.242	0.908	(-)
	KCS	10.0	1.643	1.371	1.144	(-)
		10.8	1.830	1.273	0.806	(-)
	JUMBO	14.5	1.721	1.174	0.633	(-)
	MEGA-JUMBO	16.0	1.260	1.400	1.523	(+)
	FHR Ship D	15.0	1.495	1.278	1.065	(-)
	FHR Ship F	11.6	1.409	1.361	1.314	(-)
Overall		-	**1.26 - 1.83**	**1.17 - 1.40**	**0.63 - 1.52**	
Oil Tankers	KVLCC 1	20.8	2.035	1.198	0.371	(-)
	KVLCC 2	20.8	2.018	1.204	0.400	(-)
Bulk Carriers	Japan 1704B	0.33	1.906	1.277	0.649	(-)
	JBC	16.5	1.946	1.236	0.536	(-)
	FHR Ship G	11.6	1.939	1.255	0.586	(-)
Overall		-	**1.90 - 2.03**	**1.20 - 1.27**	**0.37 - 0.65**	
LNG Carrier	KLNG	11.3	1.611	1.410	1.211	(-)

We see that hull shape is critical for these results. The bow sinkage coefficient for the group of the oil tankers and bulk carriers, which ranges between 1.90 and 2.03, on average, is 26% larger than that of the container ships, and 22% larger than the LNG carrier's value. The midship sinkage coefficient ranges from 1.17 for the JUMBO of the container ship type through to 1.41 for the KLNG. In considering the difference between C_{s_bow} and C_{s_stern} for the ships, dynamic trim for the container ships is generally quite small, but some trim quite strongly bow-down. Similar results were found in full-scale measurements on 16 container ships in Hong Kong (Gourlay and Klaka, 2007).

Theoretically, the sinkage coefficient in open water is constant for each ship, regardless of the ship speed or water depth, but does depend on hull shape. Therefore, we offer a guideline based on Table 3 for making a choice of the sinkage coefficient corresponding to different ship types. These recommended sinkage coefficients are shown in Table 4.

Table 4.
Recommended sinkage coefficients with respect to ship types in open water.

Ship Types	Sinkage Coefficient (C_s)		
	Bow (C_{s_bow})	Stern (C_{s_stern})	Max (C_{s_max})
Container Ships	1.3 - 1.8	0.6 - 1.5	1.8
Oil Tankers & Bulk Carriers	1.9 - 2.0	0.4 - 0.7	2.0
LNG Carriers	1.6	1.2	1.6

4. Limitations on using the sinkage coefficients for different bathymetries

If we wish to put limitations on using the sinkage coefficients, we can compare how the sinkage coefficient is changing with channel dimensions. We consider three idealised types of approach channel, as defined in PIANC (2014), and shown in Fig. 5.

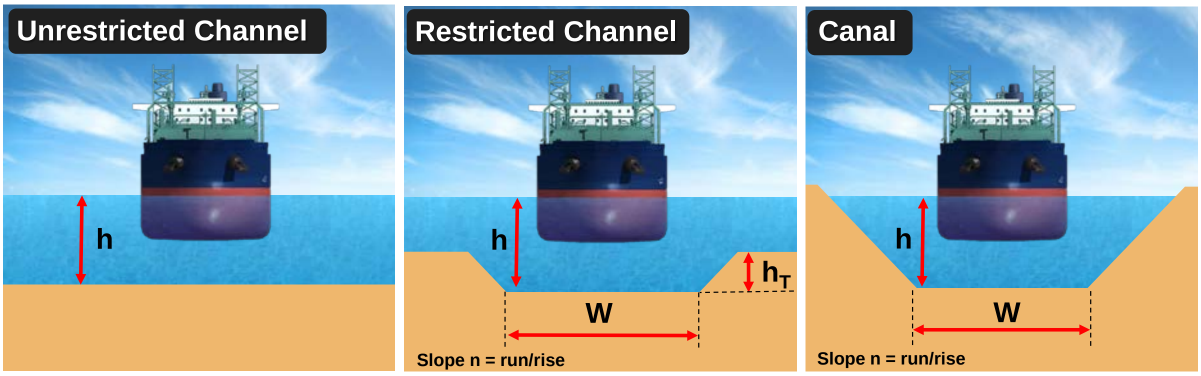

Fig. 5. Channel configurations: unrestricted (open-water); restricted (dredged); and canal.

Fig 6 illustrates relevant parameters for calculating sinkage coefficients of the ship travelling at 12 knots in the dredged channel. A 4H: 1V slope that is typical of channels dredged through surficial sandy seabeds in Western Australia is applied to both the dredged channel and canal configurations (Gourlay, 2013). The depth in the channel (including tide) and canal is set for shallow water condition of h/T = 1.2 (Jachowski, 2008; Vantorre, 2003) with varying trench depth (h_T) for the dredged channel. According to the theory, the channel width is modelled as a step depth change from channel depth (h) to outer water depth (h_O) at half-way along the slope on each side of the channel.

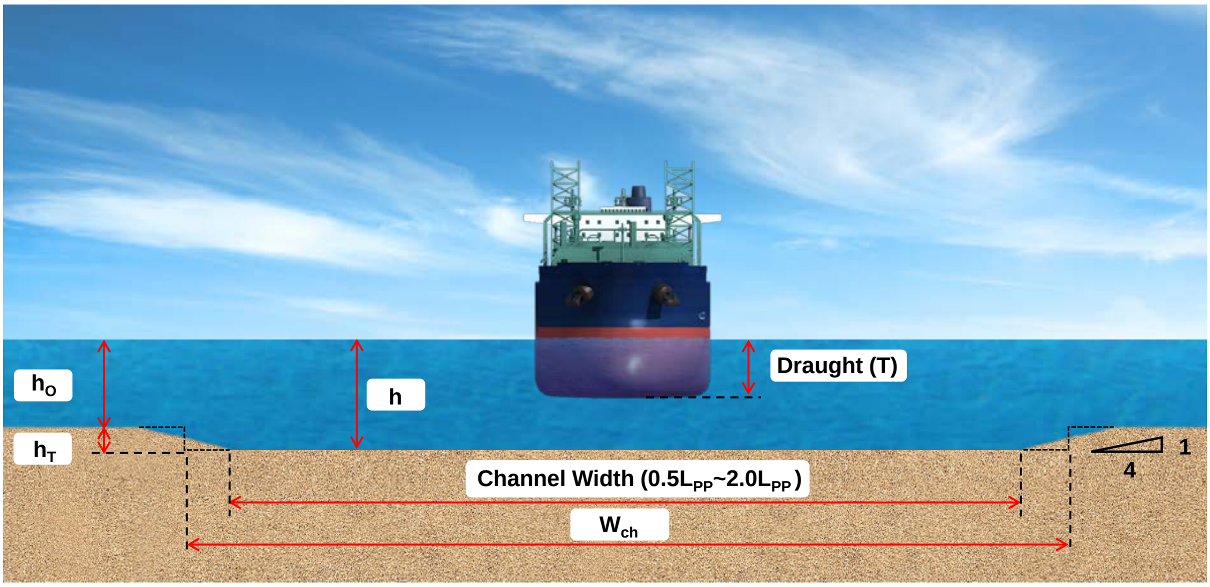

Fig. 6. Channel configuration modelled and important parameters.

The effect of different bathymetries such as channel width (to the toe of slope) and trench depth (h_T), ranging from h_T / h of 0.1 to 0.5, is shown in Fig. 7. The results plotted are the ratio of C_{s_max} to C_s in open water.

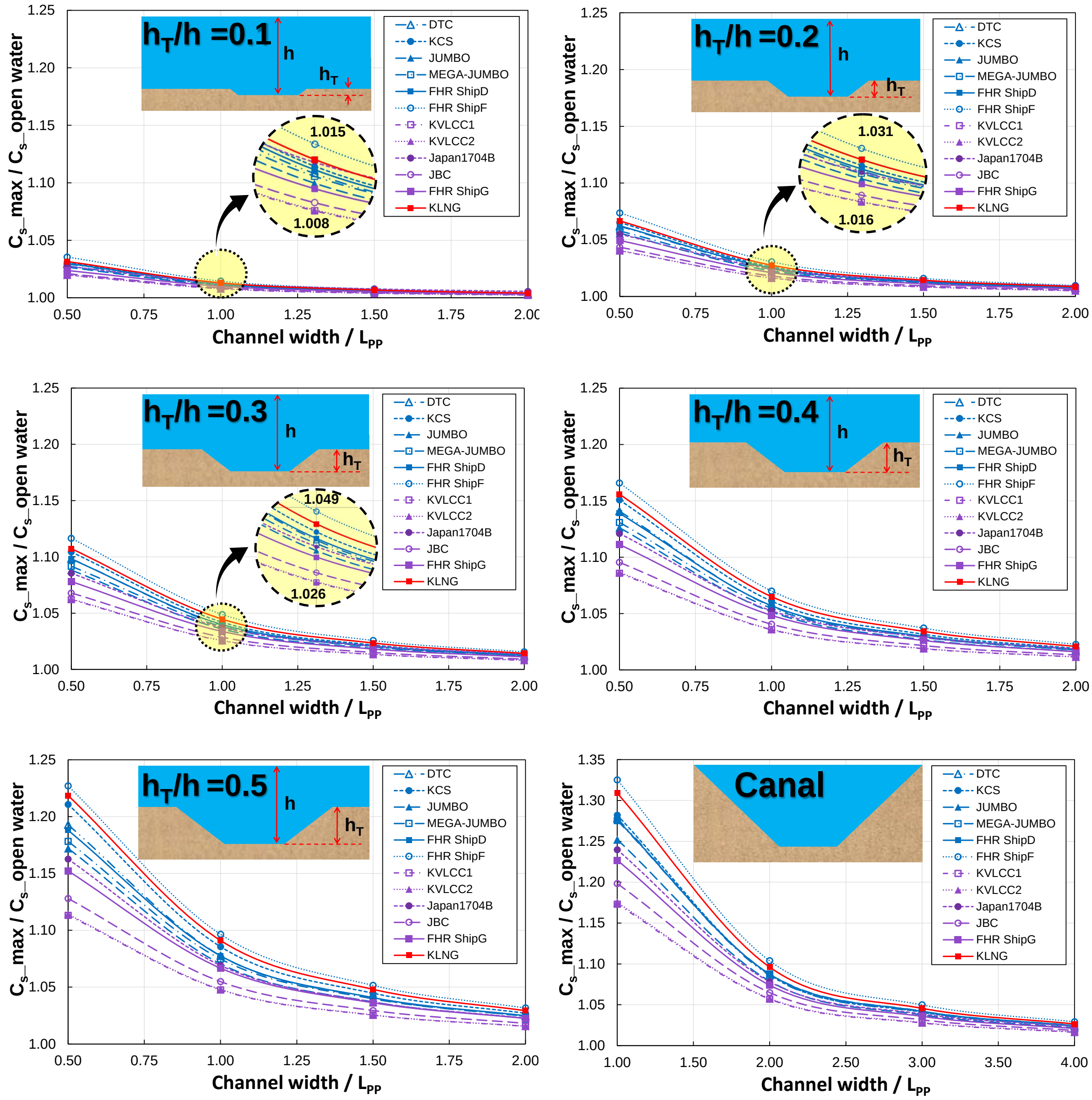

Fig. 7. Effect of transverse bathymetry on predicted sinkage coefficient.

We see in these results that the channel and canal sinkage coefficients are all larger than the open-water value, by an amount that depends on the channel bathymetry. For the most restricted case in the dredged channels (W / L_{PP} = 0.5, h_T / h =0.5), the maximum sinkage coefficient for the container ships is on average 19% larger than in open water, while that for the oil tankers and bulk carriers, and KLNG are on average 13% and 21% larger than the open-water value respectively. The difference between ship types is mainly because the transverse restriction increases the midship sinkage, but not the dynamic trim (Gourlay et al., 2015a).

Fig. 7 may be used to determine whether a particular ship and channel configuration may be classed as open water, or whether a specific narrow-channel analysis is required. For example, we may say that if the channel sinkage coefficient is within 5% of the open-water value, it is acceptable to use open-water theory. Table 5 shows this assessment for example port approach channels in Western Australia. Note that the calculations have been done at Lowest Astronomical Tide (LAT).

Table 5.
Variation from open-water conditions, for example ships and channels in Western Australia.

Port approach channel	**Fremantle (Deep Water Channel)**	**Geraldton**	**Barrow Island**
	Dredged channel (chart AUS112)	Dredged channel (chart AUS81)	Dredged channel (chart AUS66)
Channel width (w)	300m	180m	260m
Dredged depth (h)	16.4m	14.0m	13.5m
Approximate trench depth (h_T)	1.1m	3.0m	6.0m
h_T / h	0.07	0.21	0.44
Example ship	Post-Panamax container ship	Panamax iron ore carrier	KLNG membrane LNG carrier
L_{PP}	260m	215m	266m
w / L_{PP}	1.15	0.84	0.98
Maximum sinkage coefficient – variation from open-water value	~1%	~3%	~8%

Table 5 shows that the Fremantle and Geraldton channels may be classed as open water for predicting ship sinkage and trim, while a specific narrow-channel analysis would be recommended for the Barrow Island channel.

The sinkage coefficient for the canal is considerably higher than that for open-water as presented in Fig. 7. However when the canal width is equal to or greater than three times the L_{PP}, we see that canal effects are minimal, as the Tuck (1967) results are within 5% of the open water (Tuck, 1966) results.

5. Conclusions

For under-keel clearance management, sinkage coefficients have been developed for use in open waterways or dredged channels. The ships considered here for calculating the sinkage coefficients are of a broad range of ships: the DTC, KCS, JUMBO, MEGA-JUMBO, FHR Ship D, and FHR Ship F for container ships; the KVLCC1 and KVLCC2 for oil tankers; the Japan 1704B, JBC, and FHR Ship G for bulk carriers; and the KLNG for membrane LNG carriers. The following conclusions are drawn from the study:

- The sinkage coefficient in open water varies from ship hull to ship hull, but distinguishing characteristics depending on ship type are observed
- Guidelines are suggested corresponding with three categories: container ships; oil tankers/bulk carriers; and LNG carriers
- Changes in outer water depth, or trench depth, of dredged channels substantially affect ship sinkage
- Blockage effects on the ships are found to be significant in canals

Acknowledgements

The authors would like to acknowledge:

- Dr Evert Lataire and Prof. Marc Vantorre from Ghent University, and Dr Guillaume Delefortrie from Flanders Hydraulics Research, for providing hull information for the FHR Ships D, F, and G
- Dr Klemens Uliczka from BAW Hamburg, for providing hull information for the JUMBO and MEGA-JUMBO ships
- Dr Suak Ho Van from KRISO, for providing hull information for the KLNG ship

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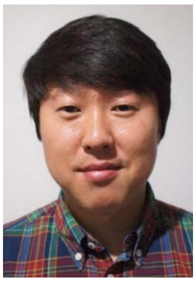

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