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Ship Squat in Non-Uniform Water Depth

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Abstract
The problem of predicting ship squat in non-uniform water depth is studied in this paper. For transverse depth variations, calculations are done using slender-body shallow-water theory, as implemented in the code "ShallowFlow". Examples are given for realistic ships transiting dredged channels, and the effect of channel width on ship squat is discussed. Further examples are given for ships transiting canals such as the new Panama Canal.

It is found that in a typical dredged channel, midship squat can be in the order of 20% larger than in open water of the same depth, while dynamic trim is essentially unchanged. In canals such as the new Panama canal, midship sinkage can be 100% larger than in open water of the same depth.

Keywords: ship UKC, squat, channel design

1. Introduction

Many port approaches utilize dredged channels, with shallow water either side of a deep channel. This has implications for ship under-keel clearance, as transverse depth restrictions tend to increase ship squat over its uniform-depth value. The effect is magnified further in wall-sided canals. As an example, model tests of Guliev [1] showed an increase of 20% for squat in a dredged channel, and an increase of 150% for squat in a canal.

In this article, we discuss the mechanisms of increased ship squat in confined water, and give example calculations for realistic test cases.

2. Theory

The theory used here is based on the slender-body shallow water theory of Tuck [2] for open water; Tuck [3] for canals and Beck et al. [4] for dredged channels. Minor changes to these theories have been made to make them more applicable to modern transom-stern ships, and the methods have been extended to cater to arbitrary transverse bathymetry, as described in [5]. The ship inputs are simply the waterline breadth and section area curve, so there is no need to mesh the hull. For commercial ships whose lines plan is confidential, the required inputs may be estimated based on representative standard series ships, modified based on information from the ship's Trim and Stability Book, as described in [6].

Validation has been done using containership model tests in rectangular and non-rectangular canals [7]; bulk carrier model tests in wide canals [8]; containerships at full-scale [9],[10]; and bulk carriers at full-scale [11].

The available experimental data has been used to develop empirical corrections to the theoretical methods, following the ICORELS procedure adopted by PIANC [12]. The resulting methods are implemented in the program "ShallowFlow" developed at CMST.

3. Flow in restricted water

Squat is essentially a Bernoulli effect, caused by local acceleration of water passing the hull, hence a drop in pressure and downward settling of the ship to achieve vertical equilibrium. With transverse depth restrictions, conservation of mass requires greater flow speeds past the ship, and hence greater pressure changes. This effect is demonstrated in Figure 1 for a Duisburg Test Case containership [13], which has principal dimensions L_{PP} = 355m, Beam = 51m, Draft = 14.5m. The ship is travelling at 10 knots, with 16m water depth in the vicinity of the ship. For the dredged channel and canal configurations, the channel width is 200m at the seabed, with a 4H:1V slope on the sides of the channel, and 8m outer water depth for the dredged channel.

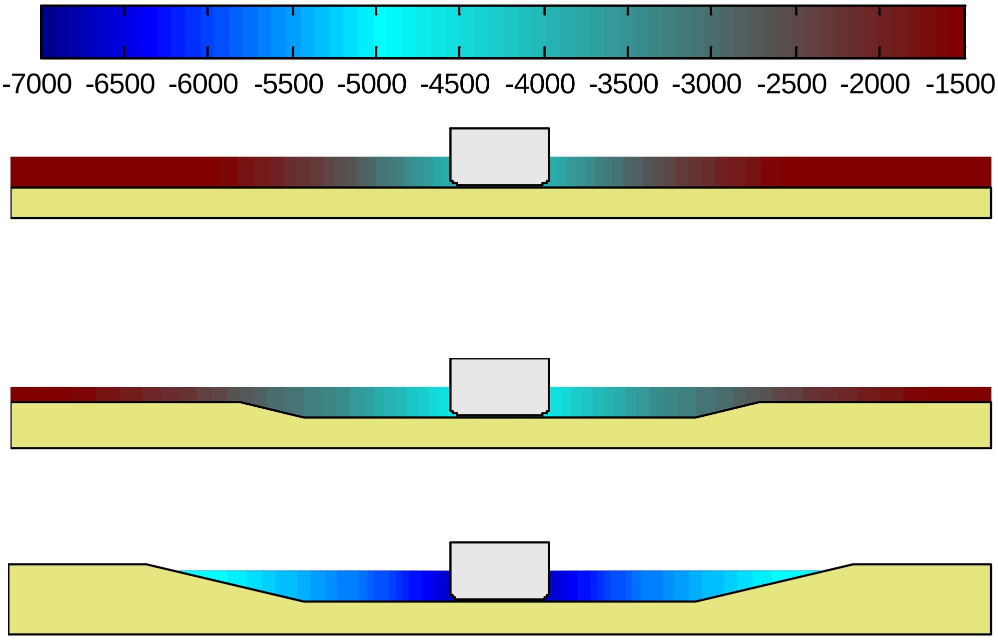

Figure 1: Pressure above hydrostatic (Pascals) at midships for a Duisburg Test Case containership in three different transverse bathymetries (open water, dredged channel, and canal), drawn approximately to scale. Restricted water has the effect of increasing the hydrodynamic pressure changes, and hence the ship squat.

4. Dredged channels

To illustrate the importance of channel parameters on ship squat, consider a bulk carrier travelling along the centreline of the dredged channel shown in Figure 2, which has a 4H:1V slope on the sides of the dredged channel. This slope is typical of channels dredged through surficial sandy seabeds in Western Australia [14].

According to the theory, this situation is modelled as a step depth change from h to h_1 at half-way along the slope on each side of the channel.

The effect of channel width W (to toe of slope) and outer depth h_1 is shown in Table 1, for a Capesize bulk carrier with L_{PP} = 290m, Beam = 50m, Draft = 17.0m and a standard series 1704B hull shape with bulbous bow [15]. The depth in the channel (including tide) is h = 20.0m.

W / h_1	170m	210m	250m	∞
8m	0.82m	0.80m	0.79m	0.73m
14m	0.77m	0.76m	0.75m	0.73m

Table 1: Bow sinkage for a Capesize bulk carrier in various dredged channel configurations

For the most confined case (W = 170m, h_1 = 8m), the midship sinkage is 19% larger than in open water of the same depth, while the trim is approximately the same, so that the bow sinkage is 12% larger than in open water of the same depth.

Similar calculations are shown in Table 2, for a Panamax 1704B bulk carrier with L_{PP} = 174m, Beam = 32.2m, Draft = 12.0m, travelling at 10 knots in a dredged channel with depth 14.0m.

W / h_1	100m	150m	200m	∞
6m	0.93m	0.88m	0.86m	0.82m
10m	0.86m	0.84m	0.83m	0.82m

Table 2: Bow sinkage for a Panamax bulk carrier in various dredged channel configurations

Again, the bow sinkage is larger in narrower dredged channels, or those with shallower water outside the channel. Note that the sinkages shown for the Panamax are greater than those of the Capesize because of the shallower water depth used for the Panamax example.

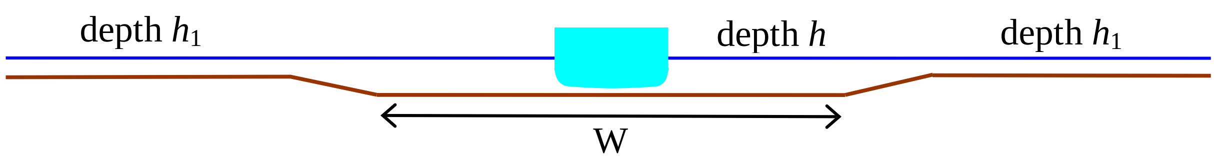

Figure 2: Bulk carrier in a dredged channel

5. Ship canals

"Canals" are defined as having finite lateral extent at the waterline. Having a restriction at the water surface, as well as a blockage underwater, considerably increases the ship squat as compared to open-water values. Various empirical methods are available for predicting squat in a canal, e.g. [16],[17]. Note that each of these empirical methods is valid for a limited range of ship types and channel dimensions, and care must be taken not to apply them outside their range of validity.

As an example of the canal effect on ship squat, let us consider a Duisburg Test Case containership [13] travelling in an idealized version of the new Gaillard Cut, Panama Canal [18]. With dimensions L_{PP} = 355m, Beam = 51m, Draft = 14.5m, this standard series hull slightly exceeds the 49m beam limitation, but is fairly representative of a New Panamax hull. A cross-section of the modelled ship and canal are shown in Figure 3, with the rock sides of the canal having a slope of 1H:1V.

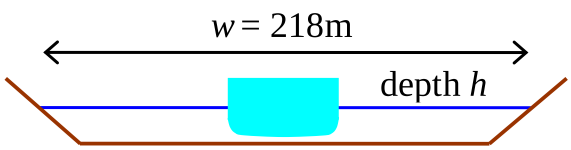

Figure 3: Duisburg Test Case containership in idealized Gaillard Cut, New Panama Canal, drawn approximately to scale

This ship and channel configuration is modelled using the arbitrary canal cross-section method of [5,§8]. Using a water depth h = 16.0m and a ship speed of 10 knots, the hydrodynamic pressure is shown in Figure 4.

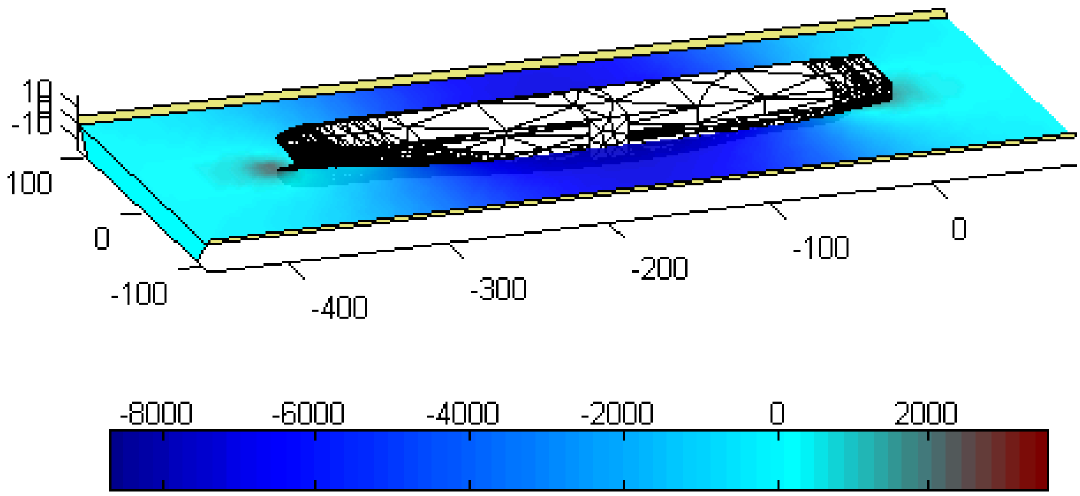

Figure 4: Pressure above hydrostatic (Pascals) for a DTC containership travelling at 10 knots in the modelled Gaillard Cut

In this case, the midship sinkage is calculated to be 1.04m, compared to 0.50m in open water of the same depth.

6. Off-centreline effects

When a ship is moving away from the centreline of a channel or canal, its squat is slightly larger than when travelling on the centreline. Lataire et al. [19, Fig. 13) presented model test results for a VLCC in a canal of width 5 times the beam. It was found for the 10% static UKC case that bow sinkage was 6% larger when the ship was moving 20% of the canal width away from the centreline, and 10% larger when the ship was at 30% of the canal width away from the centreline.

If the ship is moving off the centreline in order to pass another ship, the effect of the passing ship can be substantial. Vantorre [20],[21] conducted model tests on various types of ships passing in a wide canal, and found that maximum transient sinkage could be several times larger than the steady state sinkage. Eloot et al. [21] measured at full scale the sinkage of an Ultra-Large Container Ship (ULCS) passing another ULCS, showing a maximum transient sinkage 80% larger than the steady-state sinkage. Methods for predicting the transient squat of passing ships are described in [21] using Reynolds-Averaged Navier Stokes equations, and in [22] using slender-body shallow-water theory.

7. Longitudinal depth changes

For steady flow, squat is inversely proportional to the water depth, so that 10% decrease in water depth will result in approximately 10% increase in squat, for the same ship at the same speed.

Several model test studies have been undertaken to investigate the squat of a ship moving over a shallow bank, where unsteady effects are important. Following the grounding of the MV Wellpark in 1977 on a shoaling sandbank, Ferguson et al. [23] re-created the scenario at model scale and found that the bow sinkage slightly overshot the steady-state value as it reached the plateau of the bank. For different hull and bank configurations, Haatainen et al. [24] found that the maximum sinkage when passing over a bank was similar to the steady-state value in that water depth. Similar results were reported by Duffield [25],[26].

For longitudinal depth variations, the unsteady equations of motion are difficult to model numerically. In [27] and [28] it was found that the time-dependent slender-body shallow-water equations could only be solved accurately for simplified hull shapes with a cusped bow and stern. For these simplified ships passing a rapid depth change to shallower water, the flow was such as to produce a bow-up trim moment whilst passing into the shallower water, so that at no time was the bow or stern more likely to ground than in the uniform shallow depth. For more gradual depth changes, the results were in close agreement with a “quasi-steady” approximation in which steady-state formulae are used by inputting the instantaneous water depth at midships.

Therefore present indications are that for longitudinally-shoaling channels with rapid or gradual depth changes, the maximum squat can be conservatively estimated using the shallowest water depth encountered as input to the constant-depth formulae.

8. Summary

The problem of ship squat in non-uniform water depth has been addressed. For dredged channels, it has been found that the midship sinkage is in the order of 10-20% larger than in open water, while for canals the sinkage is much larger (e.g. 100%) than in open water. Examples have been given for a Capesize or Panamax bulk carrier in a dredged channel, and a containership in the new Panama Canal.

For longitudinal depth changes, a review has been made of previous experimental and theoretical work, which suggests that constant-depth formulae may in general be used as a conservative estimate of the transient sinkage.

9. Acknowledgement

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