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Ship Squat Predictions for Ship/Tow Simulator

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) summarizes several empirical ship squat predictions based on (Permanent International Association of Navigation Congresses (PIANC), U.S. Army Corps of Engineers, and Japanese guidance. A Fortran program was written and its use is described along with some comparisons for a typical bulk carrier and three different channel configurations.

BACKGROUND: The Corps is under increasing pressure to provide ports and waterways that can accommodate a growing economy. The Nation's existing navigation system cannot meet the projected trends in both traffic growth and vessel size. New generation mega-container ships are requiring deeper entrance channels to provide safe navigation. One of the major components of underkeel clearance is the ship squat while underway.

Squat is the reduction in underkeel clearance between a vessel at-rest and underway due to the increased flow of water past the moving body. The forward motion of the ship induces a relative velocity between the ship and the surrounding water that causes a water level depression in which the ship sinks. The velocity field produces a hydrodynamic pressure change along the ship that is similar to the Bernoulli effect in that kinetic and potential energy must be in balance. This phenomenon produces a downward vertical force (sinkage, positive downward) and a moment about the transverse axis (trim, positive bow up) that can result in different values at the bow and stern (Figure 1). Most of the time squat at the bow S_b represents the maximum value, especially for fully loaded ships with large block coefficients C_B in narrow channels or canals for high-speed ships with smaller C_B. However, maximum squat can occur at the stern S_s. The initial trim of the ship also influences the location of the maximum squat.

Prediction of ship squat depends on ship characteristics and channel configurations. The main ship parameters include ship draft, hull shape as represented by the C_B, and ship speed. The main channel considerations are proximity of the channel sides and bottom as represented by the channel depth and cross-sectional configuration. The ship is assumed to be in the center of the channel, the speed is assumed to be constant (i.e., steady-state, no acceleration), and the channel is assumed to be straight without any abrupt changes in configuration or bathymetry. Squat can exist for a ship in a transient state, for instance, when it crosses an abrupt channel depth transition sill from deep to shallower water. However, all of the ship measurements are based on a steady-state condition. Channel bends and proximity to banks tend to increase squat and muddy bottoms to decrease it.

Given the increasing costs of dredging and maintenance for many larger waterway systems and harbor projects, better relationships for prediction of squat could save tremendous amounts of Operation and Maintenance (O&M) funds. Typical costs of dredging coral or rocky entrance

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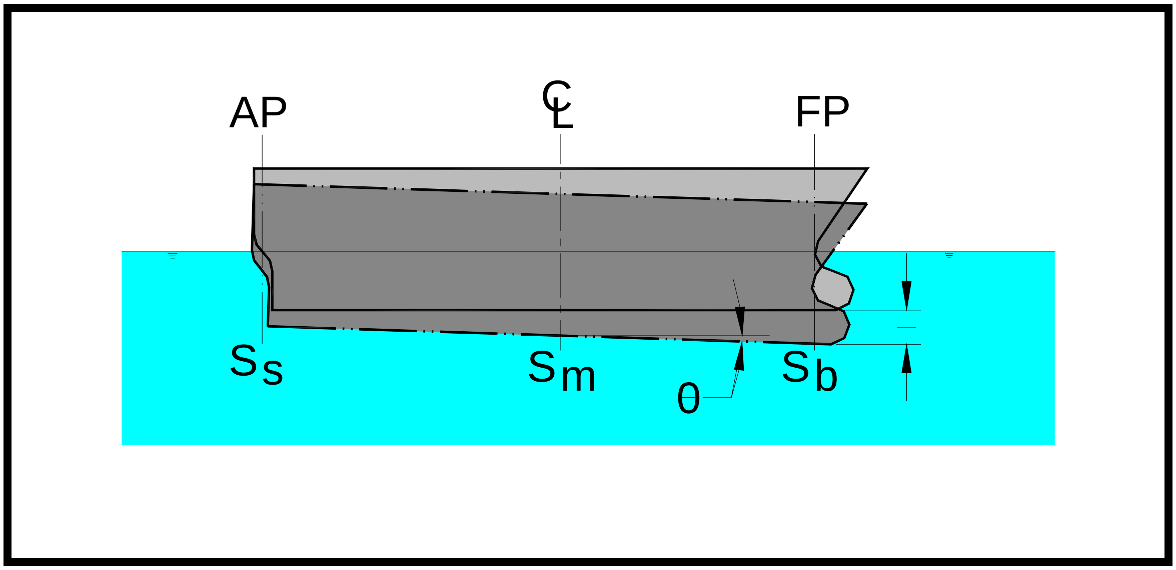

Figure 1. Ship squat definitions.

channels can exceed $1 million per foot of channel. The Port of New York is undergoing a major dredging project over the next 5 years to accommodate the increasing size of their deep-draft commercial fleet. For this location, however, dredging costs for the entire confined waterway channel can run up to $100 million per foot of depth.

Tuck (1966) conducted landmark research in this area using matched asymptotic expansions to construct approximate solutions. He derived formulas for wave resistance, vertical forces, and pitching moments for both subcritical (i.e., depth Froude number less than 1.0) and supercritical (i.e., depth Froude number greater than 1.0) ship speeds. He derived nondimensional coefficients for sinkage and trim and found that sinkage is dominant for subcritical and trim for supercritical ship speeds. His results showed satisfactory agreement with model experiments.

Beck et al. (1975) extended Tuck's (1966) work for dredged channels with shallow-water exterior regions on either side of the deeper channel. They solved boundary value problems to predict sinkage, trim, and ship resistance for subcritical ship speeds inside the channel and subcritical or supercritical speeds in the exterior regions. They found that the exterior shallow-water regions can substantially affect sinkage, trim, and wave resistance for narrow channels and increased ship speeds, especially as the exterior depths increase relative to the interior channel. The Beck et al. work has shown satisfactory correlation with a variety of different ships.

The PIANC (1997) published several empirical formulas for squat for various ship and channel configurations. The Corp's EM-1110-2-1613 (HQUSACE 2002) and the Overseas Coastal Area Development Institute of Japan (2002) have some additional formulas that are appropriate. Demirbilek and Sargent (1999) showed how much variation is possible among these different formulas. The more conservative or pessimistic predictions (i.e., larger squat values) might be more appropriate as the risk of touching bottom increases.

The purpose of this research is to incorporate these PIANC empirical formulas in the ERDC Ship/Tow Simulator (STS) so that they can be considered in their simulations. Each formula has certain constraints and conditions that it should satisfy before being applied, usually based on the conditions under which it was developed. The Beck et al. formulas will be coded and documented in a future CHETN since they require additional ship geometry information. This CHETN provides documentation of the important ship and channel input parameters, a description of these different squat formulas, and an example input and output for the new FORTRAN computer program SQUAT.

SHIP CHARACTERISTICS: Figure 2 is a schematic of a ship illustrating the main ship dimensions required for squat predictions: length between perpendiculars L_{pp}, the beam B, and the draft T. The PIANC (1997) parameter definitions are used in this CHETN where possible. The L_{pp} is measured between the forward *FP* and aft *AP* perpendiculars, and is used as an approximation to the L_w which is the vessel length at the waterline. These three dimensions are often combined into three different dimensionless ratios. The vessel length to beam ratio R_{LB} has typical values from 3.5 to 10 and is given as:

$$R_{LB} = \frac{L_{pp}}{B} \quad (1)$$

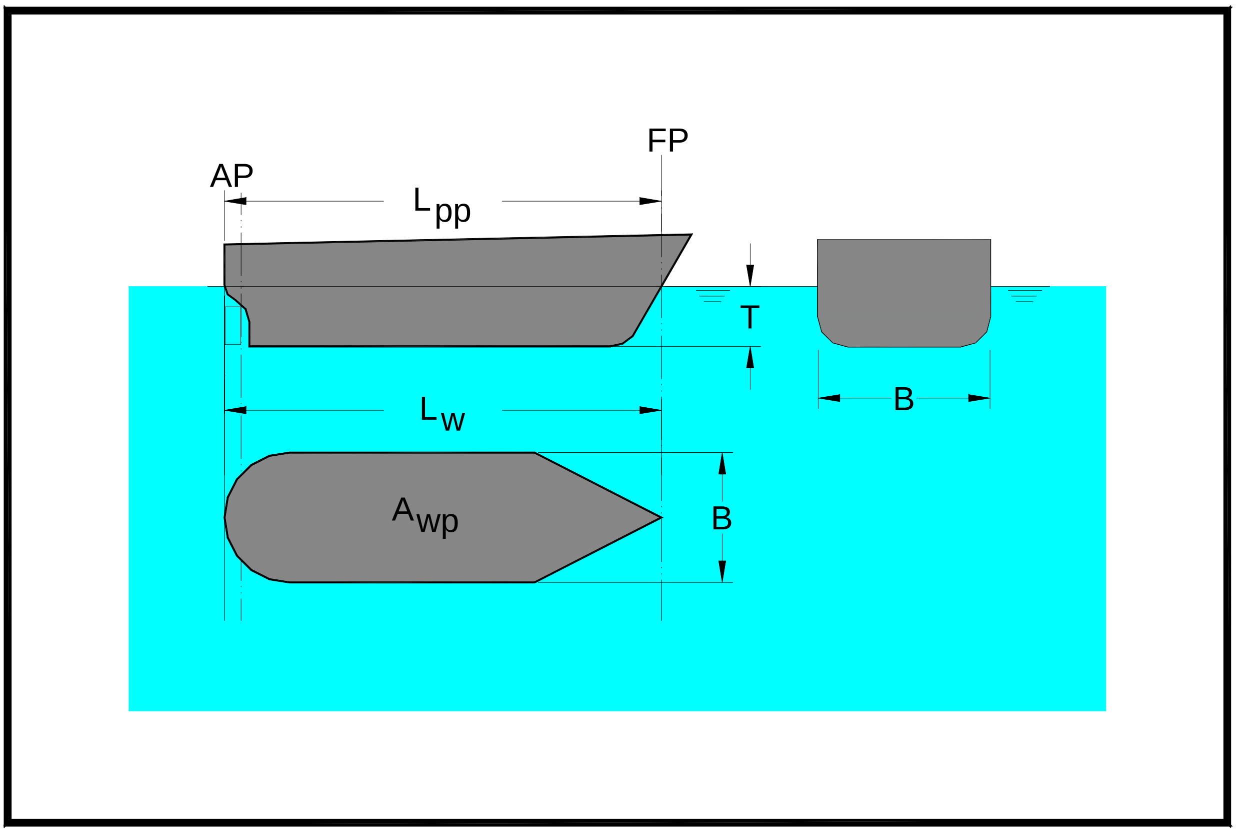

Figure 2. Ship parameters.

The vessel length to draft ratio R_{LT} has typical values from 10 to 30 and is defined as:

$$R_{LT} = \frac{L_{pp}}{T} \tag{2}$$

Finally, the vessel beam to draft ratio R_{BT} has typical values from 1.8 to 5 and is given by:

$$R_{BT} = \frac{B}{T} \tag{3}$$

Two ratios are often used to describe the hull form or overall ship shape: the block coefficient C_B and the waterplane coefficient C_{WP}. The C_B is a measure of the fineness of the vessel's shape relative to an equivalent rectangular volume with the same dimensions. Typical values of C_B are between 0.36 for high-speed vessels and 0.92 for slow, full-size tankers and bulk carriers. Container ships are slimmer and typically have C_B values in the range from 0.54 to 0.71. Additional information on C_B can be obtained from Gaythwaite (1990) and PIANC (1997).

The C_{WP} is based on the area of the vessel's waterplane cross-section A_{WP} and is defined as:

$$C_{WP} = \frac{A_{WP}}{L_{pp}B} \tag{4}$$

Again, the C_{WP} is less than 1.0 due to the fact that the actual cross-sectional area A_{WP} is divided by an equivalent rectangular area. Typical values are between 0.75 to 0.85 (Gaythwaite 1990). PIANC (1997) uses a value for C_{WP} as large as 0.90 for the larger ships. Values as large as 0.95 appear to be appropriate for the largest vessels coming on line.

Squat increases with speed for a given water depth and bank proximity. Ship speed is given by V_s in m/s and V_k in knots. Values of V_k greater than 6 knots are usually necessary to produce any significant squat.

Calculated ship parameters include the ship's displacement volume ∇ and underwater midship cross-sectional area A_S. The ∇ is defined as:

$$\nabla = C_B L_{pp} BT \tag{5}$$

The A_S =0.98BT is generally given to account for the keel radius.

CHANNEL CONFIGURATIONS: The three main types of entrance channels are as follows:

- Unrestricted or unbounded (U)
- Restricted or bounded (R)
- Canal (C)

Figure 3 is a schematic of these three types of entrance channels. Unrestricted-type channels are in larger open bodies of water and toward the offshore end of entrance channels. These are the type studied by Tuck (1966). The restricted channel, with a dredged underwater trench, is probably the most typical of U.S. channels. Canal-type channels are representative of channels in rivers. The channel sections of Beck et al. are similar to the last two, with the canal represented by a zero depth in the exterior regions. Many channels can be characterized by two or three of these channel types as the different segments or reaches of the channel have different cross sections.

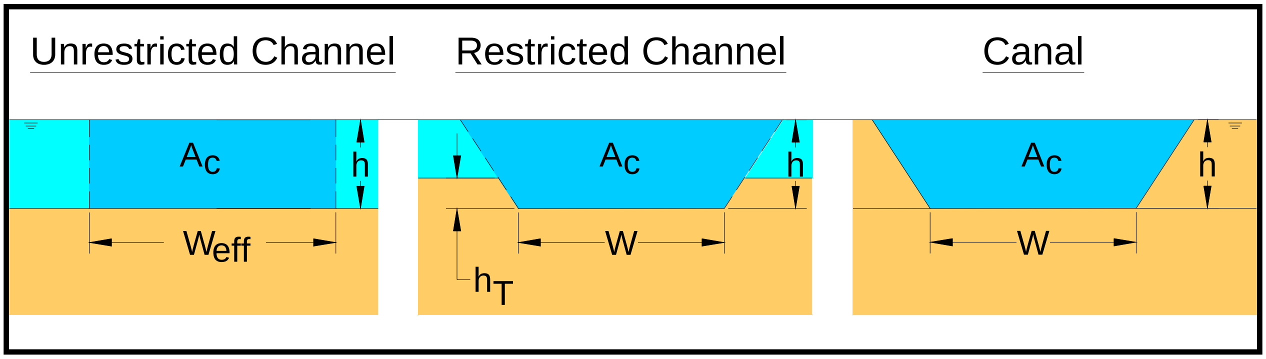

Figure 3. Types of channel configurations: unrestricted, restricted, and canal.

The important parameters are the channel width at the bottom of the channel W, water depth h, and inverse bank slope n. Table 1 indicates which parameters are necessary to describe each channel configuration. Since an unrestricted channel has no channel width W, an effective channel width W_{Eff} is calculated based on the ship's beam B and waterplane coefficient C_{WP} according to the formula originally proposed by Barrass (1979):

$$W_{Eff} = C_{Eff} B = [7.7 + 45(1 - C_{WP})^2]B \tag{6}$$

Most researchers have required W_{Eff} values of 8 or larger for unrestricted channels. The inverse bank slope is an integer like 1, 2, or 3 representing slopes of 1:1, 1:2, and 1:3, respectively.

Table 1
Channel Parameters

Parameter	**Symbol**	**Channel Type**		
		Unrestricted U	**Restricted R**	**Canal C**
Width input				
Channel width	W	--	Input	Input
Effective width	W_{eff}	Calculated	--	--
Depth input				
Water depth	h	Input	Input	Input
Height of trench	h_T	--	Input	--
Slope input				
Inverse bank slope	n	--	Input	Input
Cross-sectional area	A_C	--	Calculated	Calculated

The calculated cross-sectional area A_C is the wetted cross section of the canal or the equivalent wetted area of the restricted channel by extrapolating the slope to the water surface. It is given by:

$$A_C = Wh + nh^2 \tag{7}$$

CALCULATED SQUAT PARAMETERS: Several dimensionless parameters are required in the squat prediction formulas that are ratios of both ship and channel parameters. They include the depth to draft ratio R_{hT}, the length to depth ratio R_{Lh}, trench height to water depth ratio R_{hTh}, blockage actor S, velocity return factor S_2, and the depth Froude number F_{nh}.

The water depth to draft ratio R_{hT} is given by:

$$R_{hT} = \frac{h}{T} \tag{8}$$

A rule of thumb is to use a minimum value of R_{hT} of 1.1 to 1.15 in calm water and 1.3 to 1.5 in entrance channels when waves are present. Although these values can be larger in actual channels, the largest value in these squat formulas is assumed to be less than 2.0 for unrestricted channels.

The length to depth ratio R_{Lh} is defined as:

$$R_{Lh} = \frac{L_{pp}}{h} \tag{9}$$

The trench height h_T to water depth h ratio R_{hTh} is given by:

$$R_{hTh} = \frac{h_T}{h} \tag{10}$$

Both are measured from the bottom of the channel, so typical R_{hTh} ratios are 0.25 to 0.5.

The blockage factor S is the fraction of the cross-sectional area of the waterway A_c that is occupied by the ship's underwater midships cross-section A_s defined as:

$$S = \frac{A_s}{A_c} \tag{11}$$

Typical S values vary from 0.33 to 0.50 for restricted channels, to 0.05 or less for unrestricted channels (HQUSACE 2002).

The velocity return factor S_2 is similar to S except that it is the ratio between the ship's cross-sectional area A_s and the net cross-sectional area of the waterway A_w (Figure 4) defined as:

$$S_2 = \frac{A_s}{A_w} = \frac{A_s}{A_c - A_s} = \frac{S}{1-S} \tag{12}$$

where A_w is the difference between the channel cross-sectional area A_c and the ship cross-sectional area A_s.

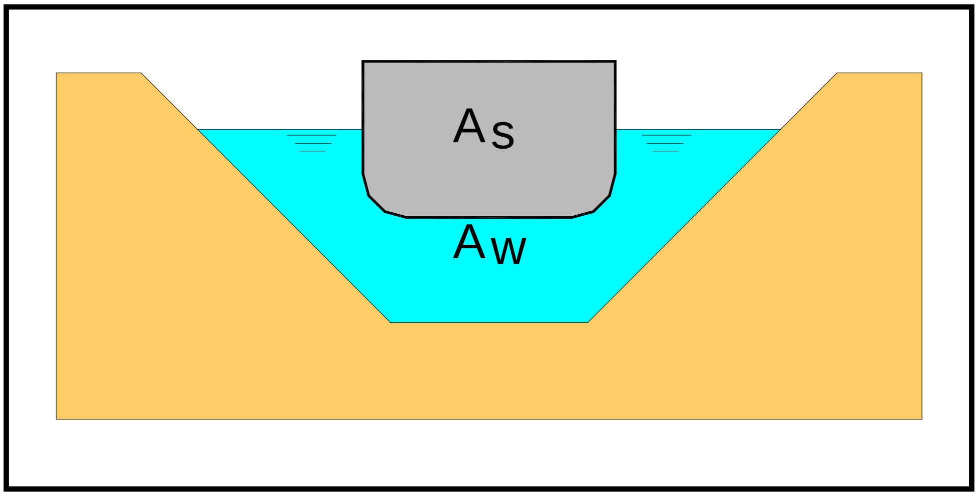

Figure 4. Velocity return factor S_2 definition.

Finally, the most important dimensionless parameter is the depth Froude number F_{nh}, which is a measure of the ship's resistance to motion in shallow water. Most ships have insufficient power to overcome F_{nh} values greater than 0.6 for tankers and 0.7 for container ships. Most of the empirical equations require that F_{nh} be less than 0.7. For all cases, the value of F_{nh} should satisfy $F_{nh} < 1$, an effective speed barrier. The dimensionless F_{nh} is defined as:

$$F_{nh} = \frac{V_s}{\sqrt{gh}} \tag{13}$$

PIANC EMPIRICAL SQUAT FORMULAS: Eleven different empirical formulas for bow squat S_b have been proposed based on physical model tests and field measurements for different channels, ships, and loading characteristics. Most are from the PIANC (1997) guidance, but the Japanese formula is from Overseas Coastal Area Development Institute of Japan (2002) and the Norrbin (1986) is from the Corp's EM 1110-2-1613 (2002).

- Barrass (1981)
- Eryuzlu and Hausser (1978)
- Eryuzlu et al. (1994)
- Hooft (1974)
- Huuska (1976)
- ICORELS (1980)
- Japanese – Overseas Coastal Area Development Institute of Japan (2002)
- Millward (1990)

- Millward (1992)
- Norrbin (1986)
- Romisch (1989)

Table 2 is a summary of the applicable channel configurations and parameter constraints according to the individual testing conditions. The Romisch is the only one that also provides stern squat S_s at the aft perpendicular. The PIANC (1997) guidance tends to favor the ICORELS (1980), Barrass (1981), and Eryuzlu et al. (1994) formulas as representative of average squat results. The Canadian Coast Guard (2001a, 2001b) is using the Eryuzlu et al. (1994) formula exclusively. The Eryuzlu and Hausser (1978) and the Romisch (1989) tend to give low values. The other formulas tend to give larger squat values that may be more useful if the cargo or bottom conditions warrant a more conservative or pessimistic outlook. PIANC recommends model tests for specific ship and channel conditions, especially if the conditions are new or novel. Many of these laboratory-based formulas are from captive towed tests that introduce unintended moments that can cause unrealistic trim of the towed models. The current thinking is to use free-floating, remote-controlled models for physical model tests. Finally, full-scale measurements are always a good check of design stage predictions.

A description of each is given in the following paragraphs, arranged in alphabetical order. These parameter constraints are programmed in the Fortran program SQUAT.

Table 2
Parameter Constraints for Squat Formulas

	Constraints			Configuration		
Code ID	C_B	*h/T*	*L/h*	**U**	**R**	**C**
Barrass (1981)	0.5 to 0.9	1.1 to 1.5		Y	Y	Y
Eryuzlu and Hausser (1978)	≥0.8	1.08 to 2.75		Y		
Eryuzlu et al. (1994)	≥0.8	1.1 to 2.5		Y	Y	
Hooft (1974)				Y		
Huuska/Guliev (1976)		1.1 to 2.0			Y	Y
ICORELS (1980)				Y		
Japanese ─ Overseas Coastal Area Development Institute of Japan (2002)						
Millward (1990)	0.44 to 0.83		6 to 12	Y		
Millward (1992)			6 to 12	Y		
Norrbin (1986)				Y		
Romisch (1989)		1.19 to 2.25		Y	Y	Y

Barrass (B). In 1979 and 1981 Barrass proposed the following formula for bow squat S_{bB} based on validation with full-scale measurements:

$$S_{b_B} = \frac{C_B S_2^{2/3} V_k^{2.08}}{30} \tag{14}$$

Barrass required the W_{Eff} be at least equal to 8 beam widths for unrestricted channels.

Eryuzlu and Hausser (E). Eryuzlu and Hausser (1978) conducted physical model tests of large, fully-loaded self-propelled tankers in unrestricted channels. They proposed the following formula for bow squat S_{bE}:

$$S_{b_E} = 0.113B\left(\frac{1}{h/T}\right)^{0.27} F_{nh}^{1.8} \tag{15}$$

Eryuzlu et al. (E2). One of the more recent series of physical model tests and field measurements was conducted by Eryuzlu et al. (1994) for cargo ships and bulk carriers with bulbous bows in restricted and unrestricted channels. Many of the early formulas did not have ships with bulbous bows. The range of ship parameters was somewhat limited with R_{LB} from 6.7 to 6.8 and B/T from 2.4 to 2.9. They conducted some supplemental physical model tests with an h_T/h=0.5 and n=2 to investigate the effect of channel width in restricted channels. Their formula for bow squat S_{bE2} is defined as:

$$S_{b_{E2}} = 0.298\frac{h^2}{T}\left(\frac{V_s}{\sqrt{gT}}\right)^{2.289}\left(\frac{h}{T}\right)^{-2.972} K_b \tag{16}$$

with gravitational acceleration g. Note that the ship draft T is used in the denominator of Equation 16, so the ratio is not the same as the F_{nh}. The K_b a correction factor for channel width given by:

$$K_b = \begin{cases} \dfrac{3.1}{\sqrt{W/B}} & \dfrac{W}{B} < 9.61 \\ 1 & \dfrac{W}{B} \geq 9.61 \end{cases}$$

The effective channel width W_{Eff} should be used for the channel width W for unrestricted channels.

Hooft (Ho). Hooft (1974) combined Tuck's (1966) separate formulations for squat from sinkage and trim in unrestricted channels to a more useful format defined by:

$$S_{b_{Ho}} = 1.96\frac{\nabla}{L_{pp}^2}\frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} \tag{17}$$

The constant "1.96" is typically used as an average value, but values from 1.9 to 2.03 are also sometimes used.

Huuska/Guliev (H). Huuska (1976) extended Hooft's work for unrestricted channels to include restricted channels and canals by adding a correction factor for channel width K_s that Guliev (1971, 1973) had developed. It is defined as:

$$S_{b_H} = 2.4 \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K_s \tag{18}$$

In general, this formula should not be used for F_{nh} greater than 0.7.

The value for K_s for restricted channels and canals is determined from:

$$K_s = \begin{cases} 7.45 s_1 + 0.76 & s_1 > 0.03 \\ 1.0 & s_1 \le 0.03 \end{cases} \tag{19}$$

with a corrected blockage factor s_1 defined as:

$$s_1 = \frac{S}{K_1} \tag{20}$$

The correction factor K_1 is given by Huuska's plot of K_1 versus S for different trench height ratios R_{hTh} shown in Figure 5. A quadratic fit of these values was calculated and is used in the Fortran program SQUAT for the Huuska formula.

ICORELS (I). The ICORELS (International Commission for the Reception of Large Ships) formula (1980) for bow squat S_{bI} is similar to Hooft's S_{bHo} and Huuska's S_{bH} equations. It is defined as:

$$S_{b_I} = 2.4 \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} \tag{21}$$

The PIANC (1997) noted that the "2.4" constant is sometimes replaced with a smaller value of "1.75" for full form ships with larger C_B.

Japanese (J). The Overseas Coastal Area Development Institute of Japan (2002) proposed the following formula for bow squat S_{bJ} as part of their new Design Standard for Fairways in Japan.

$$S_{b_J} = \left[\left(0.7 + 1.5 \frac{1}{h/T} \right) \left(\frac{C_B}{L_{pp}/B} \right) + 15 \frac{1}{h/T} \left(\frac{C_B}{L_{pp}/B} \right)^3 \right] \frac{V_s^2}{g} \tag{22}$$

Note that the L_{pp}/B and the h/T ratios correspond to the nondimensional ratios R_{LB} and R_{hT}.

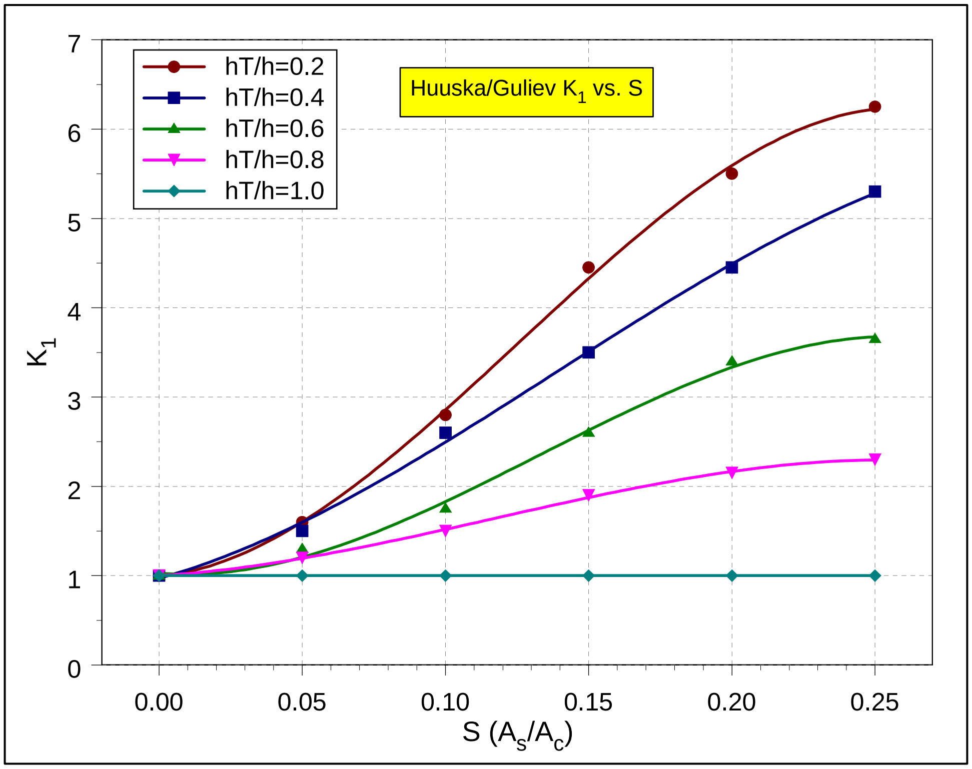

Figure 5. Huuska/Guliev correction factor K_1 vs. S.

Millward (M). Millward (1990) conducted physical model tests with towed models for several different ship types in unrestricted channels (with channel widths approximately twice the L_{pp}). Millward noted that his formula is probably conservative and errs on the side of safety as it tends to predict large squat values. He also only tested for a limited range of ship lengths, which tends to make his squat predictions of limited use for the newer and longer vessels. His formula for maximum bow squat S_{bM} is given by:

$$S_{b_M} = 0.01 L_{pp} \left(15 C_B \frac{1}{L_{pp}/B} - 0.55 \right) \frac{F_{nh}^2}{1 - 0.9 F_{nh}} \tag{23}$$

Note that the L_{pp}/B is the dimensionless ratio R_{LB}.

Millward (M2). Millward (1992) rearranged his test results and presented it in a format similar to Tuck (1966). His formula for bow squat S_{bM2} is given by:

$$S_{b_{M2}} = 0.01 L_{pp} \left(61.7 C_B \frac{1}{L_{pp}/T} - 0.6 \right) \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \tag{24}$$

Norrbin (N). Norrbin (1986) developed a formula for bow squat S_{bN} based on the work of Tuck and Taylor (1970) for a ship in an unrestricted channel. His predictions must satisfy the constraint that the $F_{nh} < 0.4$, and is thus somewhat limited in its application. It is given by:

$$S_{b_N} = \frac{C_B}{15}\left(\frac{1}{L_{pp}/B}\right)\left(\frac{1}{h/T}\right)V_K^2 \tag{25}$$

Note that two of the factors in the equation for S_{bN} are equivalent to the standard nondimensional ratios R_{LB} and R_{hT}.

Romisch (R). Romisch (1989) developed formulas for both bow and stern squat from physical model experiments for all three channel configurations. His predicted values for bow S_{bR} and stern squat S_{sR} are given by:

$$\begin{aligned} S_{b_R} &= C_V C_F K_{\Delta T} T \\ S_{s_R} &= C_V K_{\Delta T} T \end{aligned} \tag{26}$$

where C_V is a correction factor for ship speed, C_F is a correction factor for ship shape, and $K_{\Delta T}$ is a correction factor for squat at ship critical speed. The value for C_F is equal to 1.0 for the stern squat. The values for these coefficients are defined as:

$$C_V = 8\left(\frac{V}{V_{cr}}\right)^2\left[\left(\frac{V}{V_{cr}} - 0.5\right)^4 + 0.0625\right] \tag{27}$$

$$C_F = \left(\frac{10C_B}{L_{pp}/B}\right)^2 \tag{28}$$

$$K_{\Delta T} = 0.155\sqrt{h/T} \tag{29}$$

The ship's critical speed V_{cr} is based on the channel configuration and is given by:

$$V_{cr} = \begin{cases} CK_{ch} & \text{Unrestricted} \\ CK_c & \text{Canal} \\ C_{mT}\left[K_{ch}\left(1 - h_T/h\right) + K_c\left(h_T/h\right)\right] & \text{Restricted} \end{cases} \tag{30}$$

where C is wave celerity based on h, C_{mT} is a wave celerity based on the relevant water depth h_{mT} and the mean water depth h_m, K_c is a correction factor on critical speed for a canal, and K_{ch} is a correction factor on critical speed for a restricted and unrestricted channel. The two celerity parameters are defined as:

$$C = \sqrt{gh} \quad ; \quad C_{mT} = \sqrt{gh_{mT}} \tag{31}$$

with

$$h_{mT} = h - \frac{h_T}{h}\left(h - h_m\right)$$

The two correction factors K_c and K_{ch} are defined as:

$$K_c = 0.2306\log\left(\frac{1}{S}\right) + 0.0447$$

$$K_{ch} = 0.58\left[\left(\frac{h}{T}\right)\left(\frac{L_{pp}}{B}\right)\right]^{0.125} \tag{32}$$

where K_c was determined from a least square fit of Romisch's data with an R^2=0.98.

The mean water depth h_m is a standard hydraulic parameter that is only required for restricted channels and canals. It is defined as:

$$h_m = \frac{A_C}{W_{Top}} \tag{33}$$

where W_{Top} is the projected channel width at the top of the channel and is equal to:

$$W_{Top} = W + 2nh \tag{34}$$

FORTRAN PROGRAM SQUAT: The program SQUAT was written in Fortran 77 and Fortran 90 using Compaq Visual Fortran, Version 6.1. It is modular as each of the different empirical formulas is contained in its own subroutine. The input and output are in separate subroutines. The user can enter input data in two different ways: one is an interactive mode (Subroutine Input) and the other is by reading (Subroutine ReadIn) a previously stored file of the input variables. Both are performed in real-time. Input data are automatically stored (Subroutine Store) in a generic input file SquatIn.out after input is completed. The output is stored in a generic file named SquatOut.out. The user can rename these generic input and output files to save the data for later use and analysis.

The program is well documented with comments throughout. The naming convention follows the PIANC (1997) document, and other variable names are based on reasonable abbreviations of actual names. Units are in the metric system with squat in meters. The program checks the constraints for the individual empirical formulas and ship conditions to make sure the calculations are appropriate.

The first input question is whether the user wants to input (enter "I") or read in (enter "R") the data from a previously stored file. The input is the same for all three channel configurations for most of the questions, but each has some slight variations. Therefore, there are three different input files that can be renamed as necessary to the generic version. The simplest way to run the program is to pre-edit a copy of the generic input file for your own particular ship and channel conditions. Figure 6 is an example of the generic input file SquatIn.out for an unrestricted channel with a bulk carrier. This is one of the files used in the example problems described in the next section. The next question is the type of channel. The user can enter "U" for unrestricted, "R" for restricted, or "C" for canal.

These inputs are all in capital letters. If the user accidentally enters in small letters, the program will abort. The user must then restart and re-enter the input values in capital letters. The program will then run without any further action from the user.

```
   251.1600                              ! Vessel length between perpendiculars Lpp, m
   32.25000                              ! Vessel beam B, m
   12.80000                              ! Vessel draft T, m
   0.905000                              ! Vessel block coefficient CB
   10.00000                              ! Vessel speed Vk, kts
   15.36000                              ! Water depth h, m
   0.850000                              ! Waterplane coefficient CWP
Bulk Carrier, Unrestricted Channel, Cwp=0.85 to 0.90
CETN-I-63, Mar 99, Demirbilek & Sargent
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Figure 6. Example generic input file SquatIn.out for bulk carrier and unrestricted channel.

The output is first printed to the screen in a DOS Window for the user to check. The user can examine the contents as long as necessary. A carriage return will close this window. The output is then automatically written to the generic output file SquatOut.out. Figure 7 is an example for this output file. The following information is provided: title, ship input parameters, channel input parameters, calculated parameters, squat output parameters, and squat statistics. The bow squat predictions are listed in alphabetical order, followed by the Romisch stern squat prediction. Any values with “0.00” indicate a formula that was not calculated as it did not satisfy the constraints. The statistics include average, minimum, and maximum values of the predicted squat for the empirical formulas that were calculated.

Although the program was written to eventually be incorporated in the ERDC Ship/Tow Simulator software package, it is completely stand-alone at this point. Interested readers can obtain a copy of the program and input and output files by contacting the author.

EXAMPLE PROBLEM: Several example problems are presented to illustrate the effect of the different squat estimators for the three channel types. Two different ship speeds of 5 and 10 knots are used since they are representative of typical channel entrance speeds. Table 3 is a list of the different input parameters for each of the three different channel configurations. Table 4 is a summary of the output bow squat predictions for each of the applicable squat formulas.

SUMMARY: This CHETN has documented several PIANC, Corps, and Japanese empirical formulations for ship squat from their guidance. A Fortran computer program was written for use by the ERDC Ship/Tow Simulator. The individual formulas have ship and channel constraints and conditions that are required for their use. Since several of the empirical formulas are usually appropriate, an average and minimum and maximum value of squat are provided for consideration. Important ship and channel input and output parameters are described. Finally, several example input and output cases are provided for a typical bulk carrier at two ship speeds in each of the three channel types.

```
Results From Program Squat, Version 1.0
Bulk Carrier, Unrestricted Channel, Cwp=0.85 to 0.90
CETN-I-63, Mar 99, Demirbilek & Sargent


        *** Ship Input Parameters ***
        Length between perpendiculars Lpp =        251.16 m
        Beam B =                                    32.25 m
        Draft T =                                   12.80 m
        Ship speed Vk =                             10.00 kts

        *** Channel Input Parameters ***
        Channel type code CHType =                     U
        C = Canal
        R = Restricted Channel w/trench
        U = Unrestricted Channel or flat
        Water depth h =                             15.36 m
        Mean water depth hm =                       15.36 m
        Waterplane coefficient CWP =                 0.85
        Channel effective width WEff =             280.98 m

        *** Calculated Parameters ***
        Ship displacement volume Vol =           93829.36 m^3
        Coef for As bilge radius Cs =                0.98
        Area ship midship As =                     404.54 m^2
        Area channel or canal ACh =               4315.82 m^2
        Blockage factor S =                          0.09
        Velocity return factor S2 =                  0.10
        Huska factor Ks =                            1.02
        Romisch factor Cv =                          0.15
        Romisch bow factor CFb =                     1.35
        Romisch stern factor CFs =                   1.00
        Romisch factor KdT =                         0.17

        *** Squat Output Parameters ***
        Ship speed =                                 5.14 m/s
        Depth Froude No. =                           0.42
        Block coefficient CB                         0.90
        Ratio depth to draft RhT=h/T =               1.20
        Ratio ship length to depth RLh=Lpp/h =      16.35
        Bow squat, Barrass (1981) =                  0.80 m
        Bow squat, Eryuzlu & Hausser (1978) =        0.73 m
        Bow squat, Eryuzlu2 (1994) =                 0.56 m
        Bow squat, Hooft (1974) =                    0.56 m
        Bow squat, Huska (1976) =                    0.70 m
        Bow squat, ICORELS (1980) =                  0.69 m
        Bow squat, Japan (2004) =                    0.66 m
        Bow squat, Millward (1990) =                 0.00 m
        Bow squat, Millward (1992) =                 0.00 m
        Bow squat, Norrbin (1986) =                  0.00 m
        Bow squat, Romisch (1989) =                  0.44 m

        Stern squat, Romisch (1989) =                0.32 m

        *** Squat Statistics ***
        Average Bow squat SBar =                     0.64 m
        Minimum Bow squat SMin =                     0.44 m
        Maximum Bow squat SMax =                     0.80 m
        Number of squat values Npts =                   8

        Note: Zero squat ==> 1 or more constraints not satisfied
```

Figure 7. Example program Squat output file SquatOut.out for bulk carrier.

Table 3
Input Parameters for Program Squat Examples

Parameter	Symbol	Units	Channel Type		
			Unrestricted	Restricted	Canal
Vessel length between perpendiculars	L_{pp}	m	251.16	251.16	251.16
Vessel beam	B	m	32.25	32.25	32.25
Vessel draft	T	m	12.8	12.8	12.8
Vessel Block Coefficient	C_B	--	0.905	0.905	0.905
Vessel speed	V_k	knots	5 or 10	5 or 10	5 or 10
Water depth	h	m	15.36	15.36	15.36
Waterplane coefficient	C_{wp}	--	0.85	NA	NA
Channel width at bottom	W	m	NA	280.98	280.98
Bank slope (inverse)	n	--	NA	3	3
Mean water depth	hm	m	NA	15.36	15.36

Table 4
Output Bow Squat Estimates for Program Squat Examples

Squat Formula	Channel Type					
	Unrestricted		Restricted		Canal	
	5 knots	10 knots	5 knots	10 knots	5 knots	10 knots
Barrass (1981)	0.19	0.80	0.17	0.72	0.17	0.72
Eryuzlu (1978)	0.21	0.73	0.21	0.73	NA	NA
Eryuzlu et al (1994)	0.12	0.56	0.12	0.56	NA	NA
Hooft (1974)	0.13	0.56	NA	NA	NA	NA
Huuska (1976)	0.16	0.70	0.17	0.72	0.16	0.70
ICORELS (1980)	0.16	0.69	NA	NA	NA	NA
Overseas Coastal Area Development Institute of Japan (2004)	0.17	0.66	0.17	0.66	0.17	0.66
Millward (1990)	0.00	0.00	NA	NA	NA	NA
Millward (1992)	0.00	0.00	NA	NA	NA	NA
Norrbin (1986)	0.16	0.00	NA	NA	NA	NA
Romisch (1989)	0.11	0.44	0.12	0.47	0.16	0.62
Average	0.16	0.64	0.16	0.64	0.16	0.68
Minimum	0.11	0.44	0.12	0.47	0.16	0.62
Maximum	0.21	0.80	0.21	0.73	0.17	0.72
Number Averaged	9	8	6	6	4	4

This document is intended to be a living document in that it will be continually updated as new information becomes available. The Puertos del Estado (1999) has recently released new information from a major research effort on the design of ports and approach channels that is not included in existing guidance. The BAW (2005) has recently completed some physical model tests with self-propelled models for a limited range of mega-container ships and unrestricted channel configurations. Preliminary findings indicate that the existing squat formulas are not accurate for this next generation of larger, deeper draft vessels. Recognizing this potential shortcoming, the PIANC (2005) has initiated a new working group to update the 1997 PIANC guidance. Their new recommendations will be included in this computer program as they become available.

ADDITIONAL INFORMATION: For additional information, contact Dr. Michael J. Briggs, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180, (601) 634-2005, e-mail: Michael.J.Briggs@erdc.usace.army.mil. This technical note should be cited as follows:

> Briggs, M. (2006). *Ship squat predictions for ship/tow simulator*. Coastal and Hydraulics Engineering Technical Note CHETN-I-72, U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://chl.erdc.usace.army.mil/chetn/*

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