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Ankudinov Ship Squat Predictions – Part II: Laboratory and Field Comparisons and Validations

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) presents laboratory and field comparisons and validations of the Ankudinov empirical formula for ship squat. This CHETN is a continuation of Part I that documented the Ankudinov squat formulas and described two FORTRAN programs for single and multiple ship speed applications. This CHETN contains a laboratory example of a Post-Panamax containership and field measurements of four ships in the Panama Canal. It also compares the Ankudinov formula with several of the Permanent International Association of Navigation Congress (PIANC) empirical squat formulas.

BACKGROUND: This CHETN is a continuation of the earlier CHETN entitled, *Ankudinov ship squat predictions - Part I: Theory and FORTRAN programs*, CHETN-IX-19 (Briggs 2009) that documented the Ankudinov squat formulas and described two FORTRAN programs for single and multiple ship speed applications. It also compared the Ankudinov formula with several of the PIANC empirical squat formulas for a Panamax bulk carrier and tanker. This CHETN continues the comparisons in Part I with actual laboratory and field measurements for validating the relative accuracy of the predictions. Comparisons are also made with several of the more popular PIANC (1997) empirical formulas.

Two comprehensive data sets are used in these validation exercises. The Budesanstalt fur Wasserbau (BAW), Hamburg, Germany, recently completed a comprehensive series of physical model experiments with self-propelled models of Panamax and Post-Panamax containerships in a range of channel configurations (BAW 2005). The BAW (also known as the Federal Waterways Engineering and Research Institute) is the central technical and scientific agency of the Federal Waterways and Shipping Administration. Panamax and Post-Panamax containerships routinely transit German rivers to interior ports such as Hamburg.

The second validation exercise consists of field measurements of ship squat for four ships transiting the Panama Canal. In December 1997 and April 1998, the U.S. Army Engineer Research and Development Center (ERDC) measured ship squat for a number of ships that included containerships, bulk carriers, and tankers (Daggett and Hewlett 1998a and b). The 1997 study was conducted during normal canal water levels, while the 1998 study was conducted following four months of severe drought during which the Gatun Lake dropped 4 to 5 ft.

In the first section, the BAW laboratory data are compared with the Ankudinov and PIANC predictions for all three channel configurations. In the next section, the Panama Canal data are presented and discussed for a Panamax containership and a bulk carrier in the 1997 data and a Panamax tanker and containership from the 1998 measurements. The third section contains a discussion of the results. Finally, a summary is presented in the last section.

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BAW LABORATORY EXPERIMENTS: Figure 1 shows the main BAW wave basin for the investigation of ship interactions with waterways. The view of this shallow water basin is from the south end along a dock for preparing the models for testing. Figure 2 is a photograph of the model Post-Panamax containership (*Mega-Jumbo*) used in this data set. Table 1 lists the ship parameters for this model.

Figure 1. End view of BAW shallow water basin for model ship squat experiments.

Figure 2. Large Post-Panamax *Mega-Jumbo* ship model for studying ship squat in BAW laboratory. Notice the taut guide wire that extends across the basin from end to end.

Table 1. Ship parameters for BAW laboratory experiments.

Ship Name	Type	L_{pp} (m)	B (m)	T (m)	C_B	V_k (kts)	Type	W (m)	h (m)	h_T (m)	n
Mega-Jumbo	Containership	360	55	16	0.68	8-16	U	---	18	---	--
							R	392		9	4
							C	1184		---	3

Notes:
1. Tfp = Tap = T; IProp = 1, Ibow = 1, Istern = 0; KpS = 0.15, KpT = 0.15.

The BAW used a model scale of 1:40, which is adequate for minimizing boundary layer effects and maximizing measurement precision. Rotating lasers were used to measure vertical ship motions and ship squat. The ship was self-propelled, but loosely guided by a taut wire running the length of the basin (see Figure 2). This wire allows the model to move in vertical dimensions (although roll is somewhat limited), but not in horizontal sway and yaw. The models were compartmentalized with adjustable ballast and instrumented with laser reflectors, wireless antennas for data transmission, and visual targets on bow and stern. Squat measurements were obtained for unrestricted or open (U), restricted or trench (R), and canal with sides to the water surface (C) channel configurations. Channel parameters, including width at bottom (W), trench height above bottom (h_T), and inverse side slope (n), are also listed in Table 1.

BAW Results. The ANKUDINOVM4 program for multiple ship speed input was run for each of the channel configurations for the *Mega-Jumbo* containership. Figure 3 is an example of the output for the "U" channel type. Ships with $C_B \leq 0.7$ tend to squat by the stern and those with $C_B \geq 0.7$ squat by the bow. Since the C_B is close to 0.70, both bow and stern predictions are included in this example. Twelve of the PIANC (1997) empirical formulas were used to calculate averages for bow and stern squat predictions. Average PIANC values are used in the comparisons to reduce the number of plots to improve readability. Table 2 lists the formulas that were used for these predictions for each channel type. Formula constraints were enforced so that not all formulas were applicable or used in the averages for all of the configurations.

Figures 4 to 6 show Ankudinov and PIANC predictions versus measured BAW bow and stern measurements for the U, R, and C channels, respectively. The channel bottom is shown at 18 m depth or 2 m underkeel clearance (UKC) for reference. Table 3 lists minimum, average, and maximum ratios of Ankudinov and PIANC predictions to bow and stern measurements for each channel type. A ratio of 1.0 is a perfect match, whereas values greater than 1.0 indicate overprediction and less than 1.0 signify underprediction. Table 4 lists minimum, average, and maximum differences between measured and predicted bow and stern squat for each channel type. Negative values indicate underprediction and positive values imply overprediction.

In general, both the Ankudinov and PIANC ratios were worse for bow than for stern squat. The worst Ankudinov case was for the "U" channel with a range of 1.8 to 2.9 and an average overprediction of 2.3 times the measured bow squat. The best Ankudinov predictions were for the "R" channel for stern squat where ratios ranged from 1.0 to 1.6 with an average of 1.3 times the measured stern squat. The PIANC formulas tended to overpredict the bow squat and underpredict stern squat. The worst PIANC overprediction was for "R" channels with ratios ranging from 1.6 to 2.3 and average values of 1.8 times the measured bow squat. The worst PIANC underprediction was for the "C" channel with ratios ranging from 0.6 to 0.9 and averages of 0.8 times the measured stern squat. The best PIANC ratios were for the "U" and "R" stern squat with averages of 1.0 and 1.0 times the measured stern squat.

```
Results From Program AnkudinovM4, Version 4.0
BAW Mega-Jumbo Containership
Unrestricted Channel, AnkudinovM4 - 29Apr09 Changes, 30Apr09

User accepts waiver of warranty, Limitation of Liability, Indemnity, and Assent
contained in the ReadMe file for Program AnkudinovM4 and its versions


        *** Ship Input Parameters ***
        Length between perpendiculars, Lpp =        360.00 m
        Beam, B =                                    55.00 m
        Draft, T =                                   16.00 m
        Draft Forward Perpendicular, Tfp =           16.00 m
        Draft Aft Perpendicular, Tap =               16.00 m
        Block coefficient, CB =                      0.680

        *** Channel Input Parameters ***
        Channel type code CHType =                       U
        C = Canal
        R = Restricted Channel w/trench
        U = Unrestricted Channel or flat
        Water depth, h =                             18.00 m
        Channel effective width, WEff3 =            537.41 m
        Used for channel width

        *** Calculated Parameters ***
        Ship displacement volume, Vol =          215424.00 m^3
        Coef for As bilge radius, Cs =                0.98
        Area ship midship, As =                     862.40 m^2
        Area channel or canal, ACh =               9673.31 m^2
        Blockage factor, S =                         0.089

        *** Output Parameters ***
        Ratios and Constraints
        Ratio depth to draft, RhT=h/T =               1.12
        Ratio ship length to depth, RLh=Lpp/h =      20.00
        Ratio ship length to beam, RLB=Lpp/B =        6.55
        Ratio ship length to draft, RLT=Lpp/T =      22.50
        Ratio ship beam to draft, RBT=B/T =           3.44

        *** Ankudinov Output Parameters ***
        K Factors and Constants
        Single/Twin Propeller sinkage, KpS =          0.15
        Channel factor effect, Sh =                  0.054
        Channel effect, P_Ch1 =                      1.000
        Channel trim effect, P_Ch2 =                 1.000
        Single/Twin Propeller trim, KpT =             0.15
        Bulbous Bow trim, KbT =                       0.10
        Stern transom trim, KTrT =                    0.04
        Initial trim, KT1T =                          0.00
        Trim coefficient, K_Tr =                    -0.019
        Par Factors and Constants
        Hull effect shallow, Par_Hull_s =           0.0097
        Water depth effect, Par_hT_s =              1.2765


        *** Sinkage & Trim Results ***
     Speed       Fnh    Par_   Par_    SMid     Trim     SbA    SSA
   kts    mps    No.    Fnh    hT     (m/m)    (m/m)    (m)    (m)

   8.00  4.12   0.31   0.10   0.64   0.0015   0.0000   0.53   0.54
   9.00  4.63   0.35   0.13   0.59   0.0018   0.0000   0.66   0.67
  10.00  5.14   0.39   0.16   0.55   0.0022   0.0000   0.80   0.81
  11.00  5.66   0.43   0.19   0.52   0.0026   0.0000   0.95   0.96
  12.00  6.17   0.46   0.22   0.49   0.0031   0.0000   1.11   1.12
  13.00  6.69   0.50   0.25   0.46   0.0036   0.0000   1.29   1.30
  14.00  7.20   0.54   0.29   0.44   0.0041   0.0000   1.48   1.50
  15.00  7.72   0.58   0.33   0.42   0.0047   0.0000   1.69   1.71
  16.00  8.23   0.62   0.38   0.40   0.0053   0.0000   1.91   1.93
```

Figure 3. Example ANKUDINOVM4 output (metric units) for *Mega-Jumbo* BAW ship model, U channel.

Table 2. PIANC formulas used in BAW laboratory predictions.

Formula	Code	Bow			Stern		
		U	R	C	U	R	C
Barrass (2002, 2007)	Bar3	Y			Y	Y	Y
Barrass (2004)	Bar4	Y			Y	Y	Y
Eryuzlu and Hausser (1978)	E&H	Y					
Eryuzlu et al. (1994)	E2	Y	Y				
Hooft (1974)	Ho	Y					
Huuska (1976)	Hus	Y	Y	Y			
ICORELS (1980)	ICOR	Y					
Millward (1992)	Mill2	Y					
Norrbin (1986)	Nor	Y					
Römisch (1989)	Rom	Y	Y	Y	Y	Y	Y
Tuck (1966)	Tuck	Y	Y	Y			
Yoshimura (1986), OCADIJ (2002), Ohtsu et al. (2006)	Y2	Y	Y	Y			

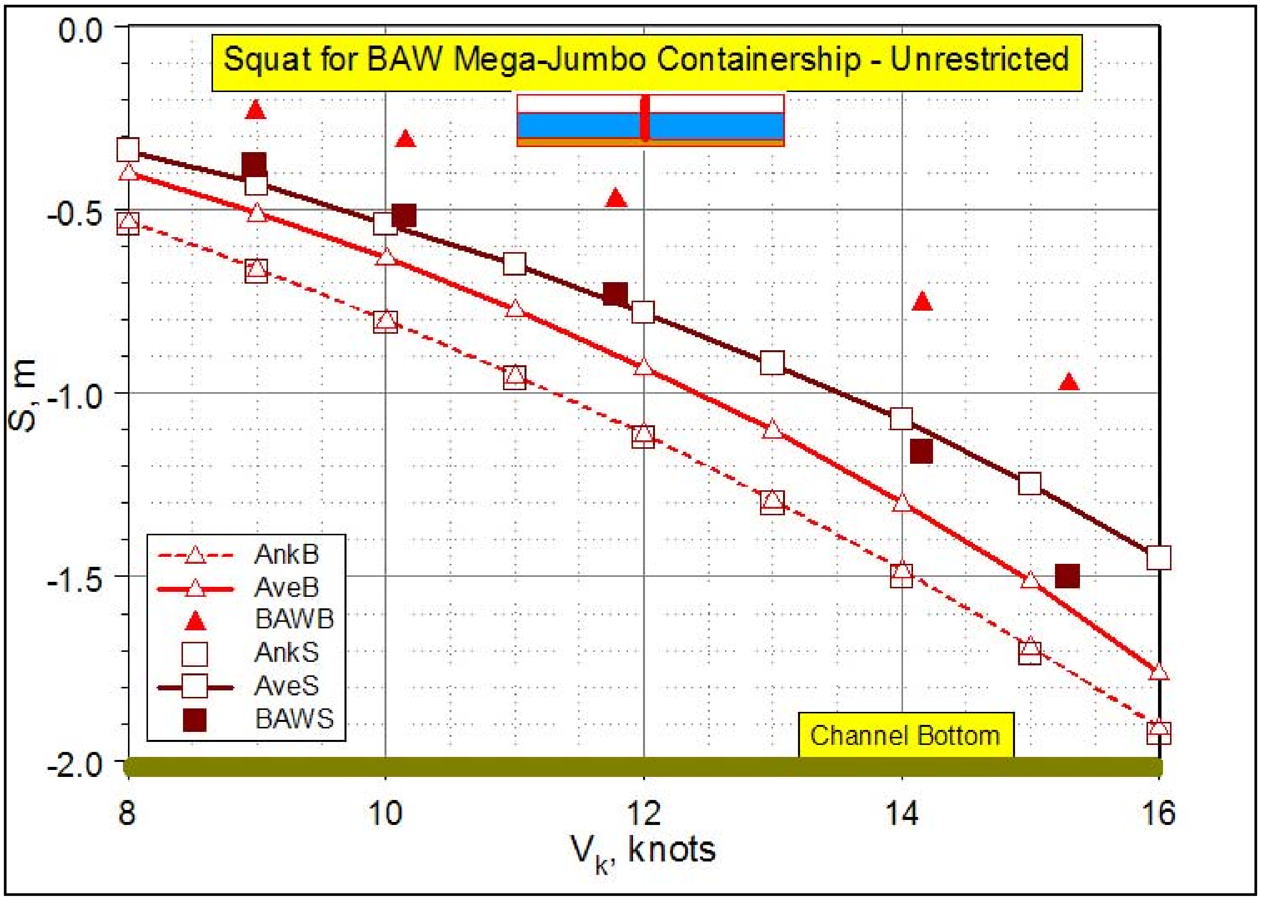

Figure 4. Ankudinov and PIANC squat predictions vs. laboratory measurements for BAW *Mega-Jumbo* containership, Unrestricted channel. BAWB and BAWS are BAW measured bow and stern squat, AnkB and AnkS are Ankudinov bow and stern predictions, and AveB and AveS are average PIANC bow and stern squat.

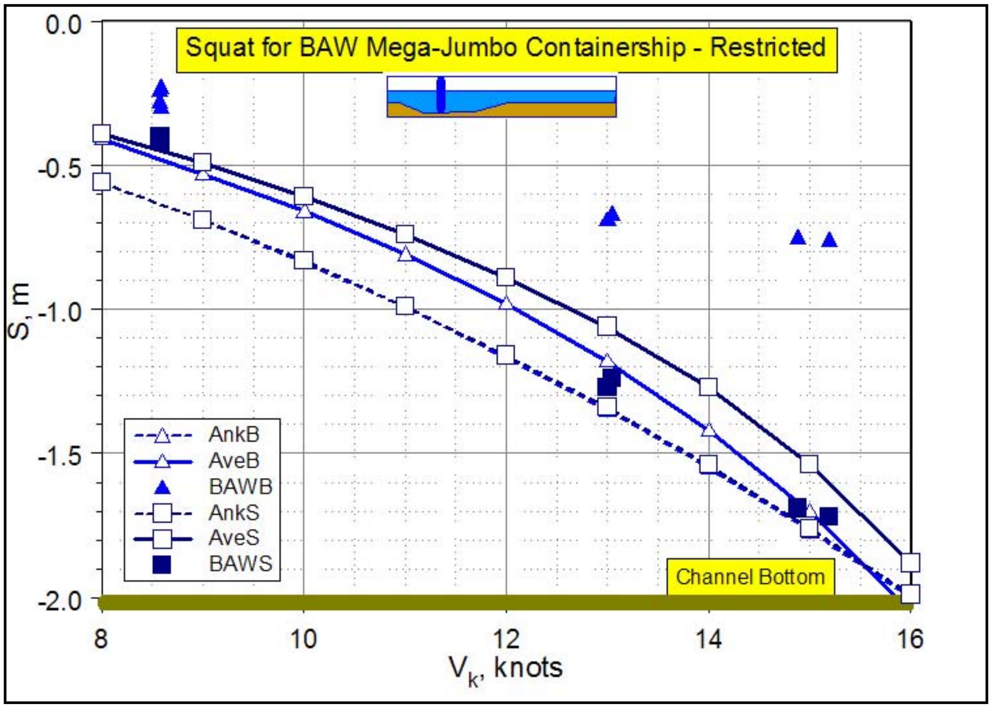

Figure 5. Ankudinov and PIANC squat predictions vs. laboratory measurements for BAW *Mega-Jumbo* containership, Restricted channel. BAWB and BAWS are measured bow and stern squat, AnkB and AnkS are Ankudinov bow and stern predictions, and AveB and AveS are average PIANC bow and stern squat.

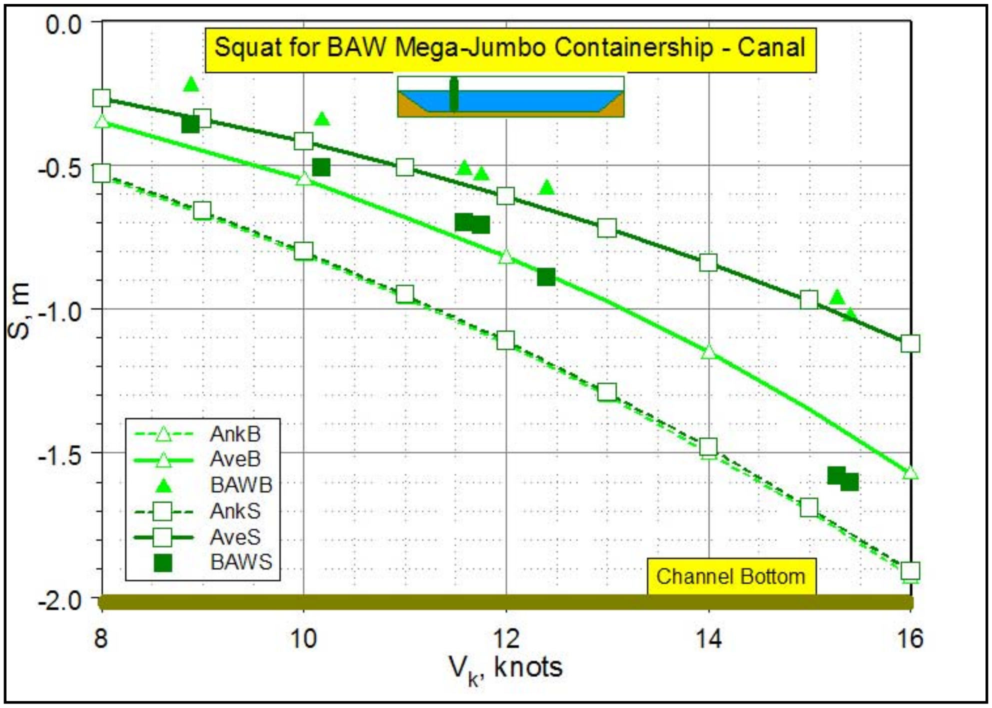

Figure 6. Ankudinov and PIANC squat predictions vs. laboratory measurements for BAW *Mega-Jumbo* containership, canal channel. BAWB and BAWS are measured bow and stern squat, AnkB and AnkS are Ankudinov bow and stern predictions, and AveB and AveS are average PIANC bow and stern squat.

Table 3. Predicted to measured bow and stern squat ratios, Ankudinov and PIANC formulas, BAW study.

Channel Type	Location	Ankudinov			PIANC		
		Minimum	Average	Maximum	Minimum	Average	Maximum
U	Bow	1.8	2.3	2.9	1.6	1.9	2.2
	Stern	1.2	1.5	1.8	0.9	1.0	1.1
R	Bow	2.0	2.2	2.4	1.6	1.8	2.3
	Stern	1.0	1.3	1.6	0.8	1.0	1.1
C	Bow	1.8	2.2	3.0	1.4	1.6	2.0
	Stern	1.1	1.4	1.8	0.6	0.8	0.9

Notes:
1. Ratio = 1.0 is prefect match
< 1.0 is underprediction
> 1.0 is overprediction

Table 4. Differences between measured and predicted bow and stern squat, Ankudinov and PIANC formulas, BAW study.

Channel Type	Location	Ankudinov (m)			PIANC (m)		
		Minimum	Average	Maximum	Minimum	Average	Maximum
U	Bow	0.4	0.6	0.8	0.3	0.4	0.6
	Stern	0.3	0.3	0.4	-0.2	0.0	0.0
R	Bow	0.3	0.6	1.1	0.0	0.4	1.0
	Stern	0.0	0.1	0.2	-0.2	-0.1	0.0
C	Bow	0.4	0.6	0.8	0.2	0.3	0.4
	Stern	0.2	0.3	0.4	-0.6	-0.3	0.0

Notes:
1. Negative value is underprediction.
2. Positive value is overprediction.

The analysis of the differences between measured and predicted values (Table 4) was similar to that for the ratios. Bow differences were larger than stern differences. The worst case Ankudinov difference occurred for the "R" channel, where the bow squat difference ranged from 0.3 m to 1.1 m, with an average 0.6 m. The smallest Ankudinov difference occurred for the stern squat for the "R" channel with average of 0.1 m. The PIANC formulas overpredicted bow squat and underpredicted stern squat. The worst PIANC overprediction was 0.4 m for average bow squat for the "U" and "R" channels. The worst PIANC underprediction was 0.3 m for average stern squat for the "C" channel.

In summary, the Ankudinov average ratios were 2.2 times larger than bow measurements and 1.4 times larger than the stern measurements. The PIANC average ratios were 1.6 to 1.9 times larger for the bow measurements and nearly exact for the stern measurements. Thus, the user should be aware that the Ankudinov model tends to be conservative.

PANAMA CANAL SHIPS: The second validation exercise involves field measurements (Ankudinov et al. 2000) made in the Gaillard Cut section of the Panama Canal (Figure 7) in December 1997 and April 1998 using the Differential Global Positioning System (DGPS). The

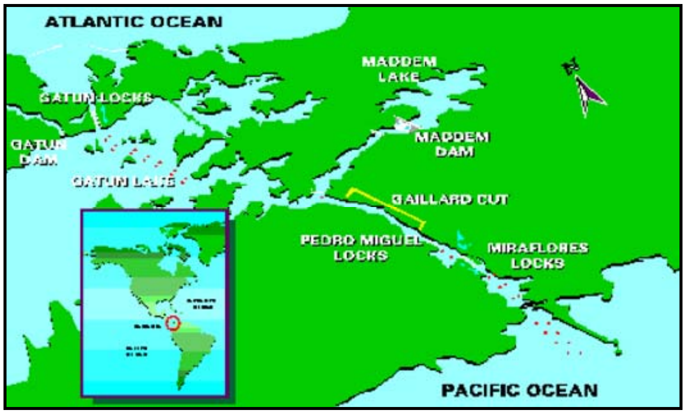

Figure 7. Location of Gaillard Cut in Panama Canal.

Figure 8. Ship transiting Gaillard Cut in Panama Canal.

Gaillard Cut (Figure 8) is a typical "canal" cross section and stretches from Culebra to Bas Obispo, a distance of approximately 30,000 ft (5 n.m.) from station location 1,670 to 1,970 (in hundreds of feet). The channel width for all transits was 500 ft. In the 1997 study, the minimum water depths in the center 300 ft of the canal were 44.6 to 49 ft, insuring a minimum UKC for the deepest draft ships of 5.1 ft. Similarly, in the 1998 study, the minimum water depths were 40.6 to 45 ft, with corresponding UKC of 3.0 ft. The DGPS measurements were made using dual frequency equipment mounted at three points on each ship (bow, and port and starboard bridge wings). The vertical accuracy levels were of the order of 1 cm.

Four of the ships from the 1997 and 1998 studies were selected for comparison with the Ankudinov predictions. Table 5 lists the parameters for these four vessels that included a Panamax tanker (*Elbe*), Panamax bulk carrier (*Global Challenger*), and Panamax containership (*Majestic Maersk*), and one containership (*OOCL Fair*) shorter than Panamax length. The ships are grouped in Table 5 according to the year of the study.

Figure 9 shows the ship speeds through Gaillard Cut. All of the ships were traveling northward from the Pacific to the Atlantic Ocean, or from right to left in this figure. When calculating ship squat, one wants to avoid acceleration and deceleration. These transits obviously have some periods with non-steady ship speeds due to maneuvering concerns and bends in the channel (there are four in this section of the Panama Canal), but are included in the averages. The *Majestic Maersk* has the largest ship speeds and the most variation in speed. The

Elbe had the smallest ship speeds since it was somewhat overloaded for the drought conditions in April 1998 and was required to go slower for the shallower depths and underkeel clearances.

Table 5. Ship parameters for Panama Canal study.

Ship Name	Type	L_{pp} (ft)	B (ft)	T_{fp} (ft)	T_{ap} (ft)	C_B	V_k (kts)
December 1997 – Minimum depth = 44.6 to 49 ft							
Majestic Maersk	Container	933.9	105.6	38.7	38.7	0.63	7-12
Global Challenger	Bulk Carrier	708.5	105.9	38.3	38.7	0.83	9-10
April 1998 - Minimum depth = 40.6 to 45 ft							
Elbe	Tanker	728.3	105.6	37	37	0.84	5-7
OOCL Fair	Container	744.7	105.6	32.2	34.8	0.65	6-10

Notes:
1. T=average of Tfp and Tap; Iprop = 1, Ibow = 1, Istern = 1; KpS = 0.15, KpT = 0.15.

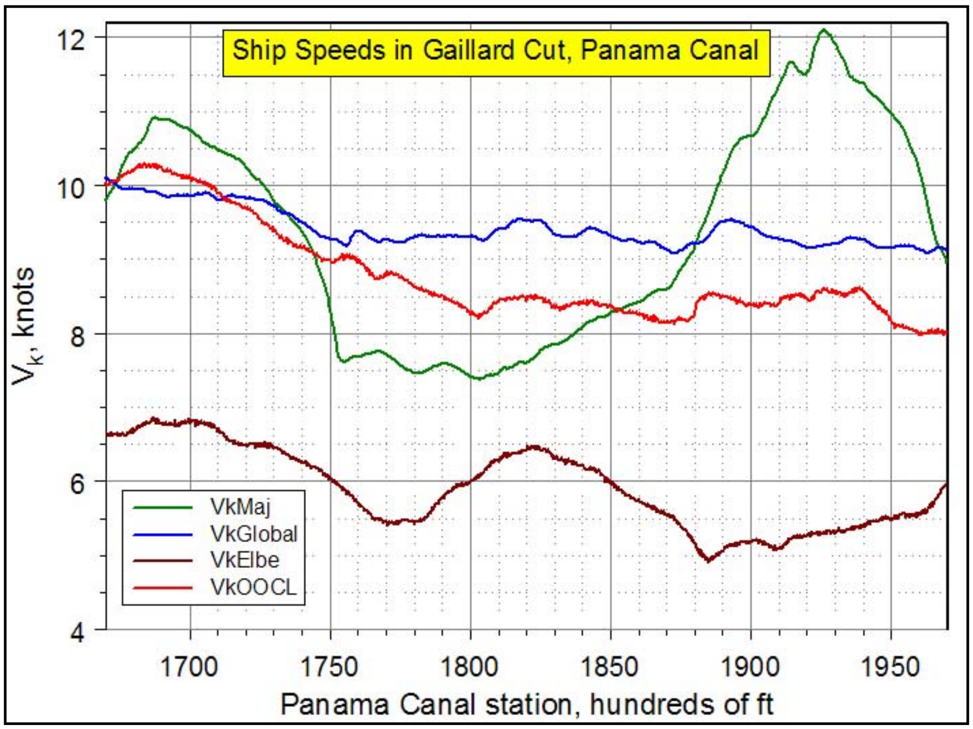

Figure 9. Ship speeds during Panama Canal transits.
All ships were northbound, sailing from right to left.

Panama Canal Results. Although FORTRAN programs had been written for the Ankudinov (Briggs 2009) and PIANC (Briggs 2006) formulas, an Excel version was created for this application due to the speed, depth, and channel area variations at each measurement location along the Panama Canal. The ANKUDINOV4 program was used as a check on the accuracy of the Ankudinov predictions at several locations for each ship. Figure 10 is an example of the output (metric units) for the *Majestic Maersk* Panamax containership at location 1,800 in Gaillard Cut. The ship speed was relatively steady in this section with a value of 7.4 knots.

```
Results From Program Ankudinov4, Version 4.0
Majestic Maersk, Canal, Test Case 2, Pt 1214, 1800 ft
Ankudinov4 - 29Apr09 Changes, 30Apr09

User accepts Waiver of Warranty, Limitation of Liability, Indemnity, and Assent
contained in the ReadMe file for Program Ankudinov4 and its versions


        *** Ship Input Parameters ***
        Length between perpendiculars, Lpp =       284.70 m
        Beam, B =                                   32.20 m
        Draft, T =                                  11.80 m
        Draft Forward Perpendicular, Tfp =          11.80 m
        Draft Aft Perpendicular, Tap =              11.80 m
        Block coefficient, CB =                     0.633

        *** Channel Input Parameters ***
        Channel type code CHType =                      C
        C = Canal
        R = Restricted Channel w/trench
        U = Unrestricted Channel or flat
        Water depth, h =                            13.05 m
        Channel width at bottom, W =               152.40 m
        Channel width, WTop =                      201.42 m
        Bank slope (inverse), n =                    1.88

        *** Calculated Parameters ***
        Ship displacement volume, Vol =          68474.54 m^3
        Coef for As bilge radius, Cs =               0.98
        Area ship midship, As =                    372.36 m^2
        Area channel or canal, ACh =              2308.65 m^2
        Blockage factor, S =                        0.161

        *** Output Parameters ***
        Ratios and Constraints
        Block coefficient, CB =                     0.633
        Ship speed, Vk =                             7.42 kts
        Ship speed, Vs =                             3.82 m/s
        Depth Froude No., Fnh =                     0.337
        Ratio depth to draft, RhT=h/T =              1.11
        Ratio ship length to depth, RLh=Lpp/h =     21.82
        Ratio ship length to beam, RLB=Lpp/B =       8.84
        Ratio ship length to draft, RLT=Lpp/T =     24.13
        Ratio ship beam to draft, RBT=B/T =          2.73

        *** Ankudinov Output Parameters ***
        K Factors and Constants
        Single/Twin Propeller sinkage, KpS =         0.15
        Channel factor, Sh =                        0.092
        Channel effect, P_Ch1 =                     1.425
        Channel trim effect, P_Ch2 =                0.538
        Trim exponent, nTr =                         3.80
        Single/Twin Propeller trim, KpT =            0.15
        Bulbous Bow trim, KbT =                      0.10
        Stern transom trim, KTrT =                   0.04
        Initial trim, KT1t =                         0.00
        Trim coefficient, K_Tr =                   -0.137

        Par Factors and Constants
        Hull effect shallow, Par_Hull_s =          0.0066
        Water depth effect, Par_hT_s =             1.2862
        Forward speed effect, Par_Fnh =            0.1222
        Propeller effect shallow, Par_hT =         0.5439

        Sinkage & Trim Results
        Mid-ship sinkage, SMid =                  0.00171 m/m
        Ship Trim, Trim =                         0.00006 m/m
        Bow Squat, SbA =                             0.48 m
        Stern Squat, SsA =                           0.50 m
```

Figure 10. Example ANKUDINOV4 output (metric units) for *Majestic Maersk* Panamax containership, Panama Canal.

Only five of the most popular PIANC (Briggs et al. 2009) formulas were included and are listed in Table 6 for each of the four ships. Appendix A contains descriptions of these PIANC formulas. The Eryuzlu formula is not strictly for canal channels, but was included since it is used by the Canadian Coast Guard for the St. Lawrence Seaway, a channel that is similar to the Panama Canal. The formula constraints were enforced so that not all formulas were available for bow and stern predictions. In fact, only the Barrass and Römisch formula were appropriate for stern predictions for canal channels, so only these two predictions were used to calculate the PIANC average for stern squat. Depending on the value of C_B, only bow or stern squat predictions were calculated. Again, the PIANC values were used to calculate an average bow or stern squat prediction at each location for each ship to compare with the measured DGPS values. Average PIANC values are used in the comparisons to reduce the number of plots to improve readability.

Table 6. PIANC formulas used in Panama Canal predictions.

Formula	Code	Bow		Stern	
		Elbe	Global	Majestic	OOCL
Barrass (2002, 2007)	Bar3	Y	Y	Y	Y
Eryuzlu et al. (1994)	E2	Y	Y		
Huuska (1976)	Hus	Y	Y		
Römisch (1989)	Rom	Y	Y	Y	Y
Yoshimura (1986), OCADIJ (2002), Ohtsu et al. 2006)	Y2	Y	Y		

Figures 11 to 14 compare Ankudinov and PIANC average bow or stern squat predictions to the measured DGPS values for the four ships along Gaillard Cut. Figure 11 illustrates the stern squat for the *Majestic Maersk* Panamax containership since this ship has a $C_B < 0.7$. The right-side axis shows the ratio of Ankudinov and PIANC predictions to measured stern squat at each location. The dashed red line is drawn for reference to indicate the idealized 1:1 ratio. Values above this line indicate overprediction, with underprediction beneath the line.

Table 7 lists the minimum, average, and maximum values of the Ankudinov and PIANC ratios for each ship for the 30,000-ft length of Gaillard Cut. A ratio of 1.0 is a perfect match, whereas values greater than 1.0 indicate overprediction and less than 1.0 signify underprediction. Table 8 lists minimum, average, and maximum differences between measured and predicted bow and stern squat for each ship. Negative values indicate underprediction and positive values imply overprediction.

For the *Majestic Maersk*, the Ankudinov ratios ranged from 0.5 to 1.7 times the measured stern squat, with an average of underprediction of 0.9. The Ankudinov differences ranged from a worst underprediction of 4.2 ft (station location 1,940) to an overprediction of 0.9 ft, and average underprediction of 0.3 ft. The PIANC ratios ranged from 0.4 to 1.6, with an average underprediction of 0.9 times the measured squat. The PIANC differences ranged from an underprediction of 3.3 ft to overprediction of 1.4 ft, with an average underprediction of 0.3 ft. From sta 1,670 to 1,850, both Ankudinov and PIANC tended to underpredict stern squat, with Ankudinov predictions slightly better. Around sta 1,880 to 1,960, the PIANC formula overpredicted stern squat. In general, both Ankudinov and PIANC tended to underpredict stern squat by 10 percent, with minimum and maximum predictions about the same.

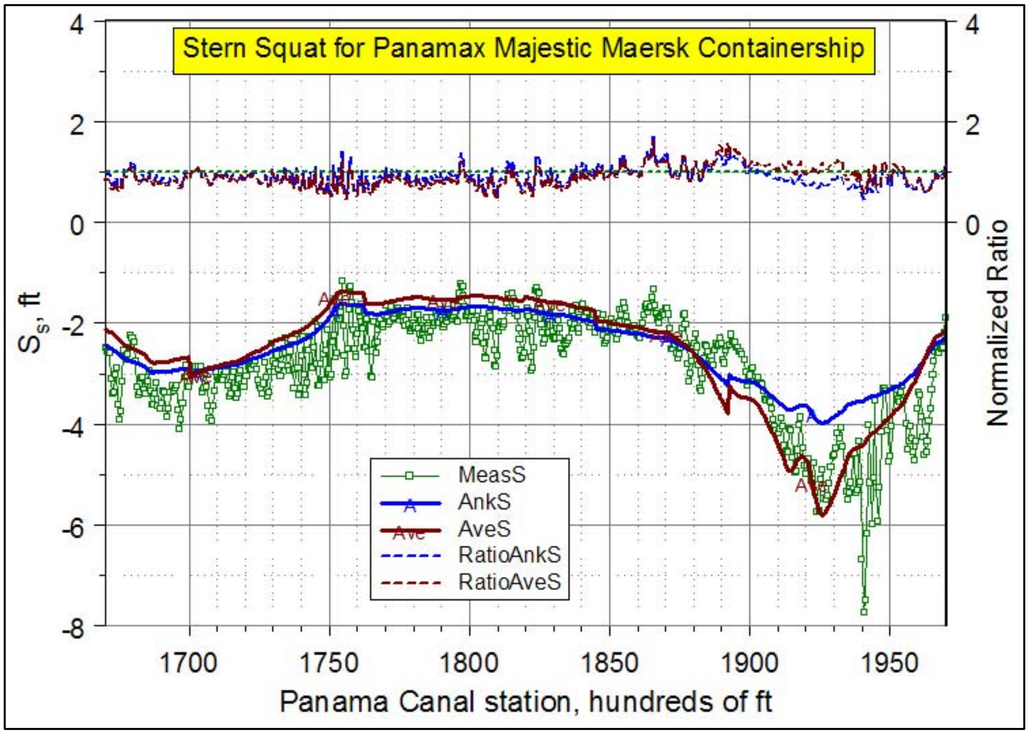

Figure 11. Measured and predicted stern squat for *Majestic Maersk* Panamax containership, Panama Canal. All ships were northbound, sailing from right to left.

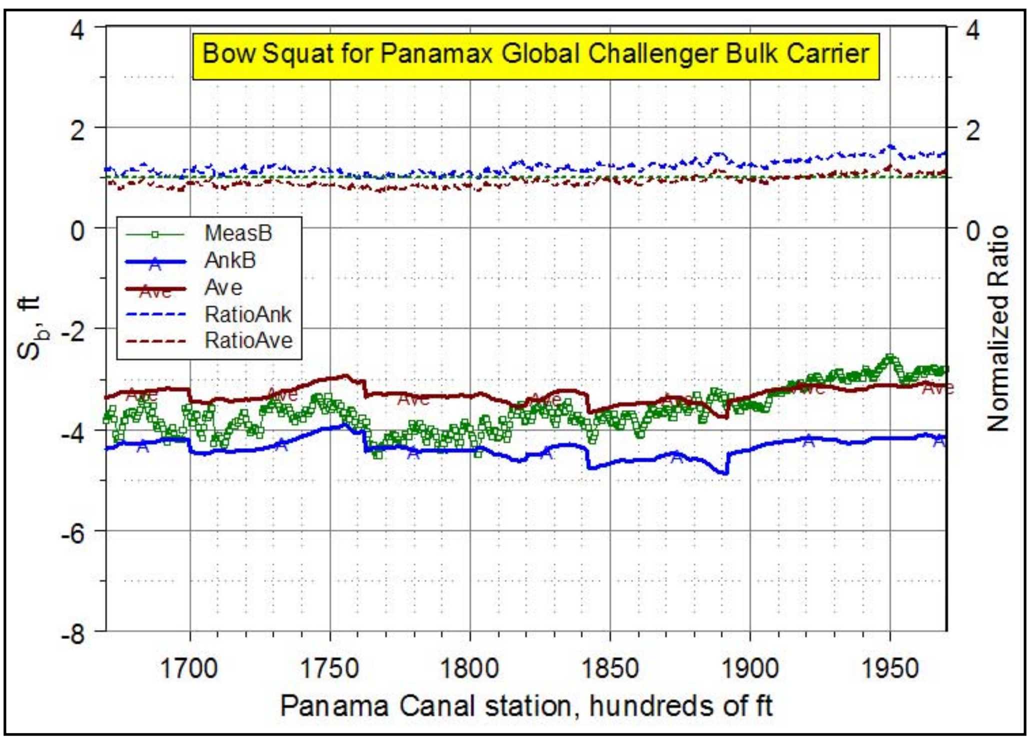

Figure 12. Measured and predicted bow squat for *Global Challenger* Panamax bulk carrier, Panama Canal. All ships were northbound, sailing from right to left.

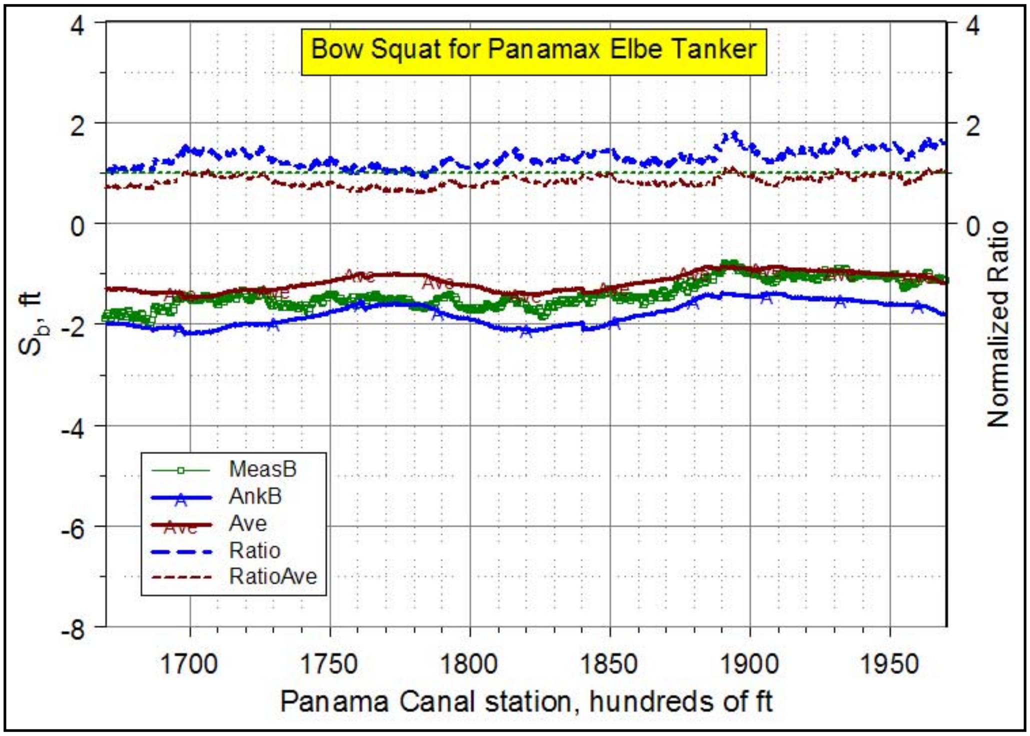

Figure 13. Measured and predicted bow squat for *Elbe* Panamax tanker, Panama Canal. All ships were northbound, sailing from right to left.

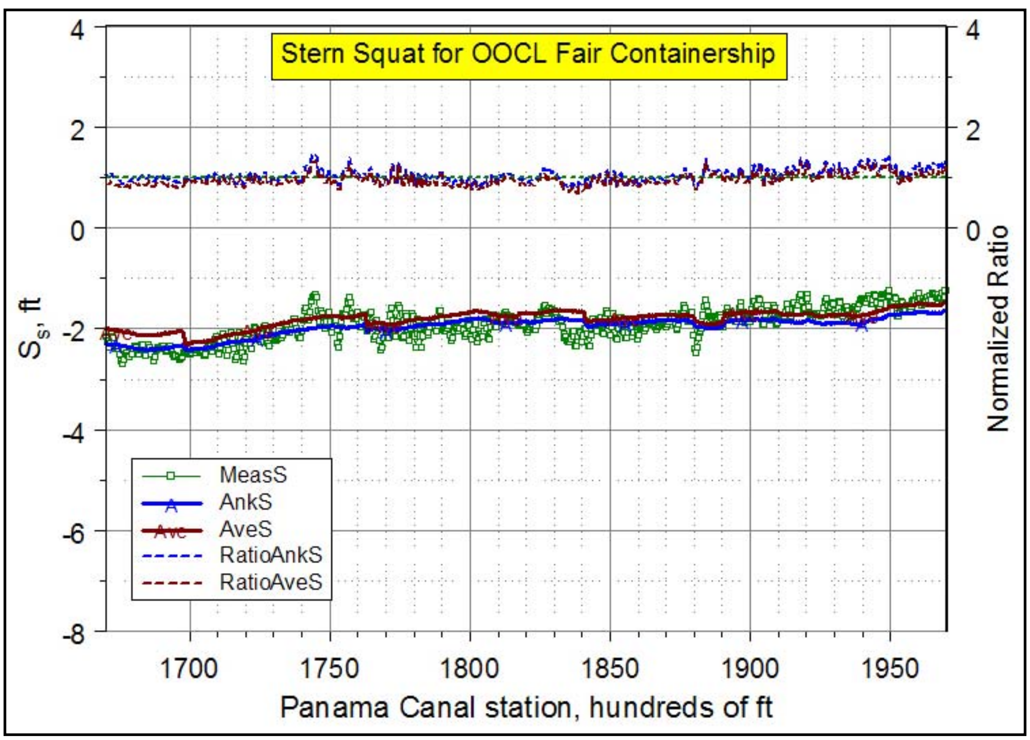

Figure 14. Measured and predicted stern squat for *OOCL Fair* containership, Panama Canal. All ships were northbound, sailing from right to left.

Table 7. Predicted to measured squat ratios, Ankudinov and PIANC formulas, Panama Canal study.

Ship Name	Location	Ankudinov			PIANC		
		Minimum	Average	Maximum	Minimum	Average	Maximum
December 1997							
Majestic Maersk	Stern	0.5	0.9	1.7	0.4	0.9	1.6
Global Challenger	Bow	1.0	1.2	1.6	0.7	0.9	1.2
April 1998							
Elbe	Bow	1.0	1.3	1.8	0.6	0.8	1.1
OOCL	Stern	0.8	1.0	1.5	0.7	1.0	1.3

Notes:
1. Ratio = 1.0 is prefect match
< 1.0 is underprediction
> 1.0 is overprediction

Table 8. Differences between measured and predicted squat, Ankudinov and PIANC formulas, Panama Canal study.

Ship Name	Location	Ankudinov (ft)			PIANC (ft)		
		Minimum	Average	Maximum	Minimum	Average	Maximum
December 1997							
Majestic Maersk	Stern	-4.2	-0.3	0.9	-3.3	-0.3	1.4
Global Challenger	Bow	-0.2	0.7	1.6	-1.3	-0.3	0.5
April 1998							
Elbe	Bow	-0.1	0.4	0.7	-0.7	-0.3	0.1
OOCL	Stern	-0.6	0.0	0.6	-0.7	-0.1	0.5

Notes:
1. Negative value is underprediction.
2. Positive value is overprediction.

Figure 12 shows the bow squat for the *Global Challenger* Panamax bulk carrier. This ship was trimmed 0.4 ft by the bow (i.e., deeper draft at the bow). In general, the Ankudinov formula overpredicted and PIANC underpredicted bow squat. Table 7 shows that the Ankudinov ratios varied from 0.0 to 2.2 times the measured bow squat, with an average overprediction of 1.2. The differences between measured and predicted squat ranged from underpredictions of 0.2 ft to overpredictions of 1.6 ft, with an average underprediction of 0.7 ft for the Ankudinov formula. The PIANC ratios with five formulas in the calculations were closer to the measured bow squat, especially above the location at station 1,850. They ranged from 0.7 to 1.2 times the measured squat, with an average underprediction of 0.9. The PIANC differences ranged from an underprediction of 1.3 ft to an overprediction of 0.5 ft, with an average underprediction of 0.3 ft. The PIANC formulas overpredicted the measured squat for a short section from location 1920 to 1970. Thus, the Ankudinov formula averaged 20 percent and 0.7 ft overprediction and the PIANC 10 percent and 0.3 ft underprediction. For design purposes, overprediction is more conservative and potentially safer.

Figure 13 shows the bow squat for the *Elbe* Panamax tanker. Table 7 lists a range of Ankudinov ratios ranging from overpredictions up to 1.8, with an average of 1.3 times the measured bow squat. The Ankudinov differences ranged from underprediction of 0.1 ft to overpredictions of 0.7 ft, with an average overprediction of 0.4 ft. The PIANC averages ranged from 0.6 to 1.1 times the measured bow squat, with an average underprediction of 0.8. The PIANC differences ranged from an underprediction of 0.7 ft to an overprediction of 0.1 ft, with an average underprediction of 0.3 ft. In general, the Ankudinov formula overpredicts by 30 percent and 0.4 ft while the PIANC underpredicts by 20 percent and 0.3 ft. Again, overpredictions would be more conservative design.

Finally, Figure 14 shows the stern squat for the *OOCL Fair* containership. This ship had the most trim with a value of 2.6 ft by the bow. Table 7 lists a range of Ankudinov ratios from 0.8 to 1.5 times the measured stern squat, with an average ratio of 1.0 (an exact match with measured data). The Ankudinov differences ranged from both under and overpredictions of 0.6 ft, with an average of 0.0 ft (exact match). The PIANC ratios varied from underpredictions of 0.7 to overpredictions of 1.3, with an average of 1.0 (exact match) times the measured stern squat. The PIANC differences ranged from an underprediction of 0.7 ft to an overprediction of 0.5 ft, with an average underprediction of 0.1 ft. Thus, the Ankudinov predictions were about the same as the PIANC predictions in this case, and both very good.

Overall for the Panama Canal data, the Ankudinov formula overpredicts squat by 25 percent for the bow and underpredicts by 5 percent for the stern while the PIANC underpredicts squat by 15 percent for both bow and stern. All of the data were used in the comparisons even though there are a lot of turns or bends in this section of canal. Ships experience acceleration, deceleration, and roll in turns that affects squat.

DISCUSSION: The limited set of comparisons with PIANC and measured data indicates that the Ankudinov formulas are conservative in most instances. The PIANC predictions are based on averages (sometimes only one or two formulas for stern squat). In some instances, one or more of the PIANC formulas might match measured data much better than the averages. The Ankudinov formulas are some of the most complicated to use and based on an attempt to include every factor in a coherent and organized manner. The main Ankudinov advantage is that a designer would rather have a slight overprediction than underprediction.

SUMMARY: This CHETN has compared and validated the Ankudinov ship squat predictions with laboratory and field measurements. The Ankudinov formulation is the main ship squat formulation in the ERDC Ship/Tow Simulator. The Ankudinov predictions were validated with BAW laboratory data of a Post-Panamax *Mega-Jumbo* containership in three channel configurations and DGPS measurements of four ships in the Gaillard Cut section of the Panama Canal. These ships included a Panamax containership, Panamax bulk carrier, and Panamax tanker and a containership. The measured data were also compared with several of the PIANC empirical formulas for bow and stern squat. This CHETN is a continuation of Part I that documented the Ankudinov squat formulas and described two FORTRAN programs for single and multiple ship speed applications.

In general, the Ankudinov formulas overpredicted the BAW laboratory data by an average of 2.2 times bow data and 1.4 times the stern measurements for all three channel types. The corresponding PIANC averages were 1.8 and 0.9 for bow and stern predictions, respectively. For the Panama Canal data, the Ankudinov formulas overpredicted measured bow squat by a factor of

1.25 and underpredicted stern squat by a factor of 0.95. Again, PIANC underpredicted squat by 0.85 for both bow and stern. Thus, the Ankudinov predictions are slightly larger than the PIANC predictions, although the Ankudinov predictions match canal channel types like the Panama Canal better than PIANC.

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> Briggs, M. J., and L. Daggett. 2009. *Ankudinov ship squat predictions – Part II: Laboratory and field comparisons and validations*. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IX-20, Vicksburg, MS: U.S. Army Engineer Research and Development Center, *http://chl.erdc.usace.army.mil/chetn/*.

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APPENDIX A: PIANC SHIP SQUAT FORMULAS FOR PANAMA CANAL

This appendix contains a description of the five empirical PIANC squat formulas used in the Panama Canal comparisons with Ankudinov squat predictions for a canal (C) channel. In general, only the PIANC formulas that are representative of the Panama Canal are discussed. Ships tend to squat at the bow S_b for $C_B > 0.7$ or stern S_s when $C_B \leq 0.7$. All PIANC formulas provide S_b, but only the Barrass and Römisch provide S_s.

BARRASS (B3): Barrass (2002, 2004, 2007) is on his fourth iteration of ship squat formulas. The one in this CHETN is considered his third version (B3) for both S_b and S_s as a function of C_B. It is defined as:

$$\frac{KC_B V_k^2}{100} = \begin{cases} S_b & C_B > 0.7 \\ S_S & C_B \leq 0.7 \end{cases} \tag{1}$$

Barrass's channel coefficient K is based on analysis of over 600 laboratory and prototype measurements for all three channel types. It is defined as:

$$K = 5.74 S^{0.76} \qquad 1 \leq K \leq 2 \tag{2}$$

The blockage factor S is a measure of the relative cross-sectional area of the ship to that of the channel defined as:

$$S = \frac{A_s}{A_c} \tag{3}$$

where A_s and A_c are ship and channel cross-sectional areas, respectively. The A_S is:

$$A_S = 0.98BT \tag{4}$$

The A_c is a projection of the channel sides to the water surface. For C channels A_c is given by:

$$A_c = Wh + nh^2 \qquad \text{C} \tag{5}$$

However, for the Panama Canal comparisons, the measured A_c was used.

ERYUZLU ET AL. (E2): Eryuzlu et al. (1994) developed his formula for S_b based on laboratory experiments. Although it is usually restricted to unrestricted (U) and restricted (R) channels, it is included in these comparisons since the Canadian Coast Guard uses it for ships in the St. Lawrence Seaway, a channel that is similar to the Panama Canal. It is defined as:

$$S_b = 0.298 \frac{h^2}{T} \left(\frac{V_s}{\sqrt{gT}} \right)^{2.289} \left(\frac{h}{T} \right)^{-2.972} K_b \tag{6}$$

where the factor K_b is a correction factor for channel width, W, as a function of channel type and ship beam B.

$$K_b = \begin{cases} \dfrac{3.1}{\sqrt{W/B}} & \dfrac{W}{B} < 9.61 \\ 1 & \text{U or } \dfrac{W}{B} \geq 9.61 \end{cases} \tag{7}$$

HUUSKA/GULIEV (HG): The next empirical squat formula was developed by Huuska (1976) and Guliev (HG) for S_b. It is given by:

$$S_b = C_S \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} K_s \tag{8}$$

with C_S=2.4 and ship displacement ∇ equal to:

$$\nabla = C_B L_{pp} B T \tag{9}$$

The channel width correction factor K_s is defined as:

$$K_s = \begin{cases} 1.0 & s_1 \leq 0.03 \\ 7.45 s_1 + 0.76 & s_1 > 0.03 \end{cases} \tag{10}$$

where the corrected blockage factor s_1 for C channels is given by:

$$s_1 = S \qquad \text{C} \tag{11}$$

RÖMISCH (R1): Römisch (1989) developed formulas for both S_b and S_s from physical model experiments for all three channel configurations. His S_b and S_s are defined as:

$$S_b, S_s = C_V C_F K_{\Delta T} T \tag{12}$$

The factors in this equation are correction factors for ship speed C_V, ship shape C_F, and squat at critical speed $K_{\Delta T}$ defined as:

$$C_V = 8\left(\frac{V}{V_{cr}}\right)^2 \left[\left(\frac{V}{V_{cr}} - 0.5\right)^4 + 0.0625\right] \tag{13}$$

$$C_F = \begin{cases} \left(\dfrac{10 B C_B}{L_{pp}}\right)^2 & \text{Bow} \\ 1.0 & \text{Stern} \end{cases} \tag{14}$$

$$K_{\Delta T} = 0.155\sqrt{h/T} \qquad (15)$$

Critical ship speed V_{cr} is a function of channel configuration and is defined for C channels as:

$$V_{cr} = CK_C \qquad \text{C} \qquad (16)$$

where wave celerity C is a function of the water depth for canals given by:

$$C = \sqrt{gh_m} \qquad \text{C} \qquad (17)$$

The mean water depth h_m is a function of the projected width at the top of the channel W_{Top} defined as:

$$h_m = \frac{A_C}{W_{Top}} = \frac{A_C}{W + 2nh} \qquad (18)$$

However, the h_m was provided for the Panama Canal data, so that value was used.

Finally, the correction factor K_C is given by:

$$K_C = \left[2\cos\left(\frac{\pi}{3} + \frac{Arc\cos(1-S)}{3}\right)\right]^{1.5} \qquad (19)$$

YOSHIMURA (Y2): The last squat formula was developed by Yoshimura (1986) as part of Japan's Design Standard for Fairways in Japan. It was enhanced by the Overseas Coastal Area Development Institute of Japan (OCADIJ 2002) and Ohtsu et al. (2006) to include predictions for R and C channels. It is defined for S_b as:

$$S_b = \left[\left(0.7 + \frac{1.5T}{h}\right)\left(\frac{BC_B}{L_{pp}}\right) + \frac{15T}{h}\left(\frac{BC_B}{L_{pp}}\right)^3\right]\frac{V_e{}^2}{g} \qquad (20)$$

where the enhanced ship speed term V_e for C channels is given by:

$$V_e = \frac{V_s}{(1-S)} \qquad \text{C} \qquad (21)$$