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AN EMPIRICAL MODEL FOR SHIP-GENERATED WAVES

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Objectives
Ship-Generated Wave Heights

- Develop empirical equation to predict maximum wave heights generated by conventional ships
- Improve upon existing predictive equations:
  - Sorensen and Weggel (1984) & Weggel and Sorensen (1986)
  - PIANC (1987)
- Use existing data published in the literature
- Run new lab tests to supplement existing data
- Run field trials to verify empirical model
  - Tests conducted in Chesapeake Bay April 2005

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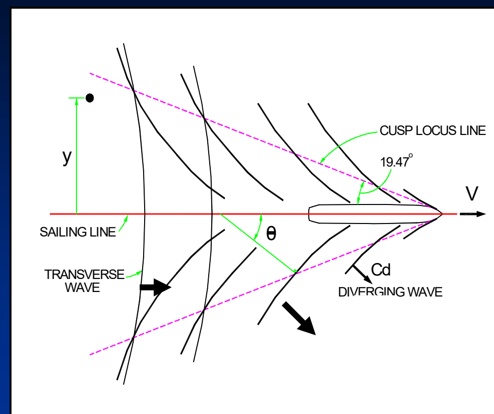
Definitions

- Two wave systems:
  - Diverging Waves
  - Transverse Waves
- Maximum wave heights
  - Form along "Cusp Line"
  - Vary with distance from sailing line, y



SAMPLE SHIP-GENERATED WAVE PATTERN FOR DEEP WATER (after Sorensen, 1997)

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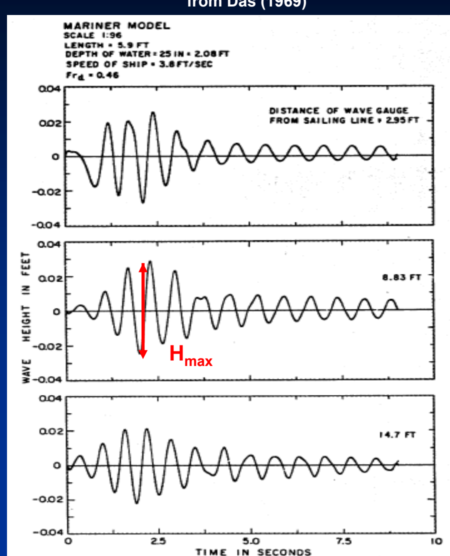
Sample Wave Records from Literature

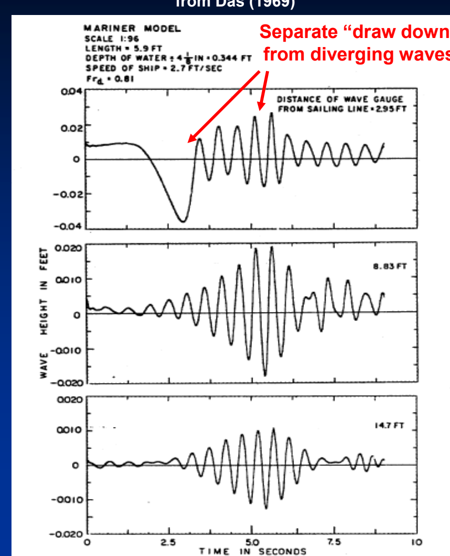
Deep Water

from Das (1969)



Shallow Water

from Das (1969)



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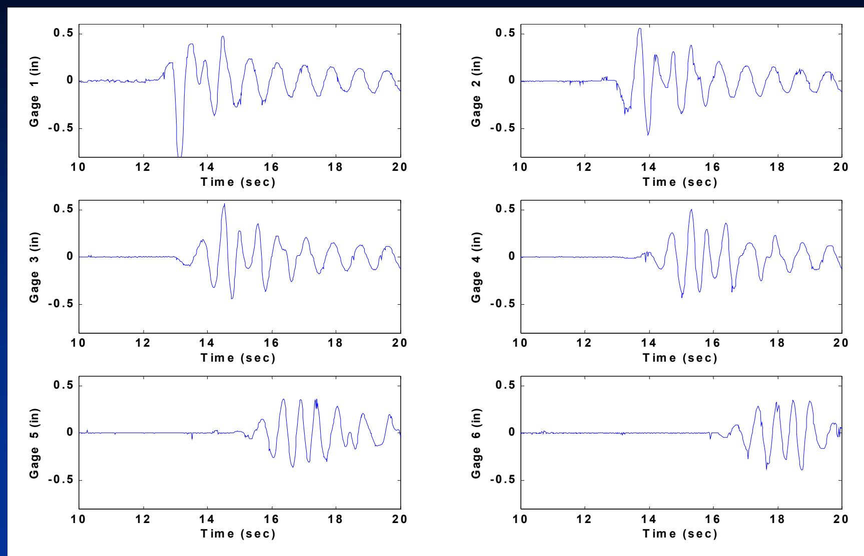
Examples from Naval Academy Tests

Waves measured at 6 distances y off sailing line



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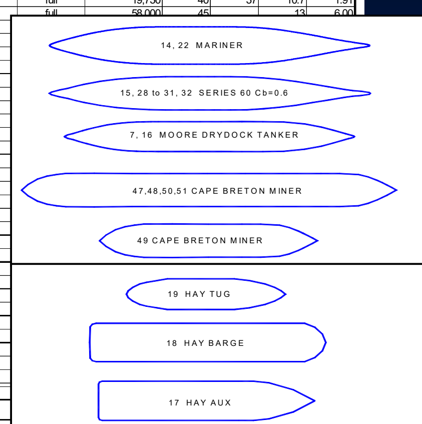
Ship Wave Database

Ship Number	Investigator	Scale for Rx=10 m	Vessel	Scale	Displacement (lbs)	Length (feet)	Lwl (feet)	Beam (feet)	Draft (feet)
1	Sorensen (1973)	8.73	Cabin Cruiser	full	6,000	23		8.3	1.70
2		8.58	Coast Guard Cutter (40-FOOT)	full	19,730	40	37	10.7	1.91
3		3.71	Tugboat	full	58,000	45		13	6.00
4		5.29	Air-Sea Rescue Vessel						
5		1.87	Fireboat						
6		1.18	Barge						
7		0.77	Moore Dry Dock Tanker						
8	Sorensen (1966)	185.59	Model A						
9		139.12	Model B						
10		111.40	Model C						
11		92.80	Model D						
12		69.61	Model E						
13		77.83	Weinblum hull						
14	Hay (1967)	76.11	Mariner Class Cargo Ship						
15		81.58	SERIES 60 Cb=0.6						
16		74.05	Moore Dry Dock Tanker						
17		58.20	Auxiliary Supply Vessel						
18		57.02	Barge						
19		47.88	Tug						
20	Bidde (1968)	76.11	Mariner Class Cargo Ship (A)						
21			Barge (E)						
22	Das (1969)	76.11	Mariner Class Cargo Ship						
23			Cruiser						
24	Zabawa & Ostroa (1980)		Uniflight Cruiser						
25			Boston Whaler						
26	Kurata & Oda (1984)	64.76	Ferryboat						
27			Tugboat						
28	USNA (2000)	78.58	SERIES 60 Cb=0.6 MID						
29	USNA (2000)	75.40	SERIES 60 Cb=0.6HEAVY						
30	USNA (2000)	83.10	SERIES 60 Cb=0.6 LIGHT						
41	Helwig (1966)		Empress of Canada (Ocean Liner)						
42	Helwig (1966)		M.S. Wearfield (Ocean Freighter)						
47	Carruthers (1966)	73.54	Cape Breton Miner Bulk Carrier No Bulb						
48	Carruthers (1966)	44.28	Cape Breton Miner Bulk Carrier No Bulb	1:57.8	347.992	11.763	11.16058	1.2456	0.449745
49	Carruthers (1966)	44.28	Cape Breton Miner Bulk Carrier No Bulb SHORT	1:57.8	191.718	7.092146	6.489276	1.2456	0.449745
50	Helwig (1966)	71.56	Cape Breton Miner Bulk Carrier Bulb	1:96	81	7.0833	6.72	0.75	0.286
51	Helwig (1966)	71.56	Cape Breton Miner Bulk Carrier No Bulb	1:96	81	7.0833	6.72	0.75	0.286



Ship wave data used in present analysis:

2100 data points for 12 ships

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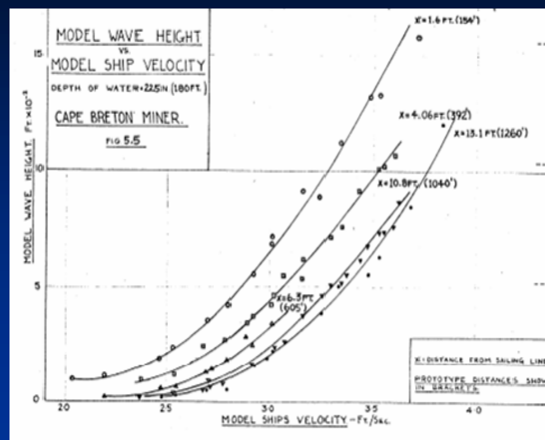
Sample Wave Data from Literature

- Wave heights for a given ship hull form characterized by:
  - Length, L
  - Beam, B
  - Draft, D
  - Hull Form
- Wave Heights vary with:
  - Ship speed, V
  - Distance from sailing line, y
  - Water depth, d



(FROM HELWIG, 1966)

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Normalizing Wave Measurements

- Wave height normalized by velocity head

  gH/V^2
- Distance from sailing line can be normalized in many ways (with various length scales L, B, etc) ...we use:

  y/L
- Data in shallow water organized by depth-to-draft ratio

  D/d
- Velocities normalized as Froude Number

  $F_d = V/(gd)^{1/2}$ or $F_L = V/(gL)^{1/2}$

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Empirical Model
Variation of *H* with Distance from Sailing Line

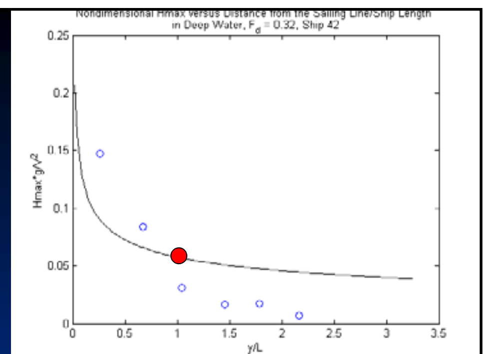
- Havelock (1908) theory for deep water:
  - $H \sim y^{-1/3}$ for diverging waves
  - $H \sim y^{-1/2}$ for transverse waves
- Empirical evidence in literature shows a range from
  - $H \sim y^{-0.25}$ to $H \sim y^{-0.6}$
- Present study:
  - Least–squares fit of both -1/3 and -1/2 models to data
  - Model using -1/3 power gave best fit
    - C varies with ship hull form, T/D, F_d or F_L

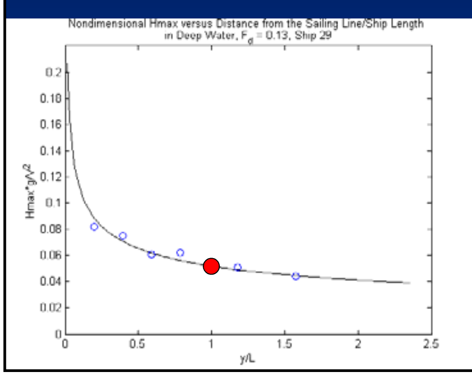
$$\frac{gH}{V^2} = C\left(\frac{y}{L}\right)^{-1/3}$$

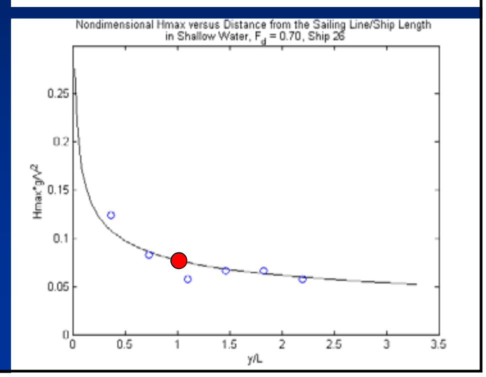
Examples of Fit

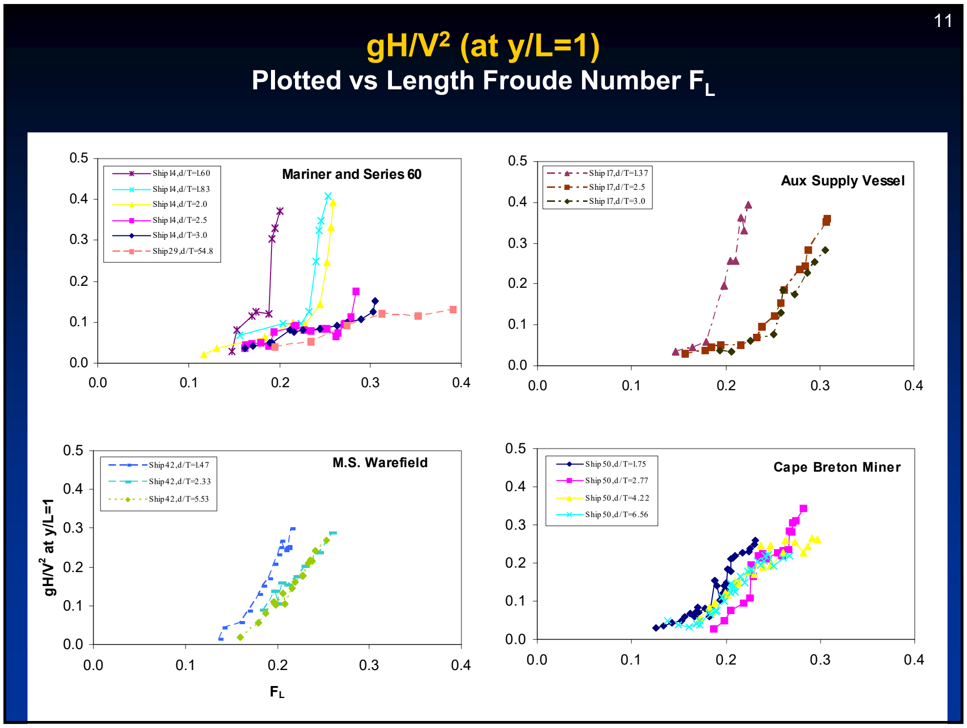
gH/V^2 versus $(y/L)^{-1/3}$

Value of gH/V^2 at y/L=1 used as a characteristic value for further analysis





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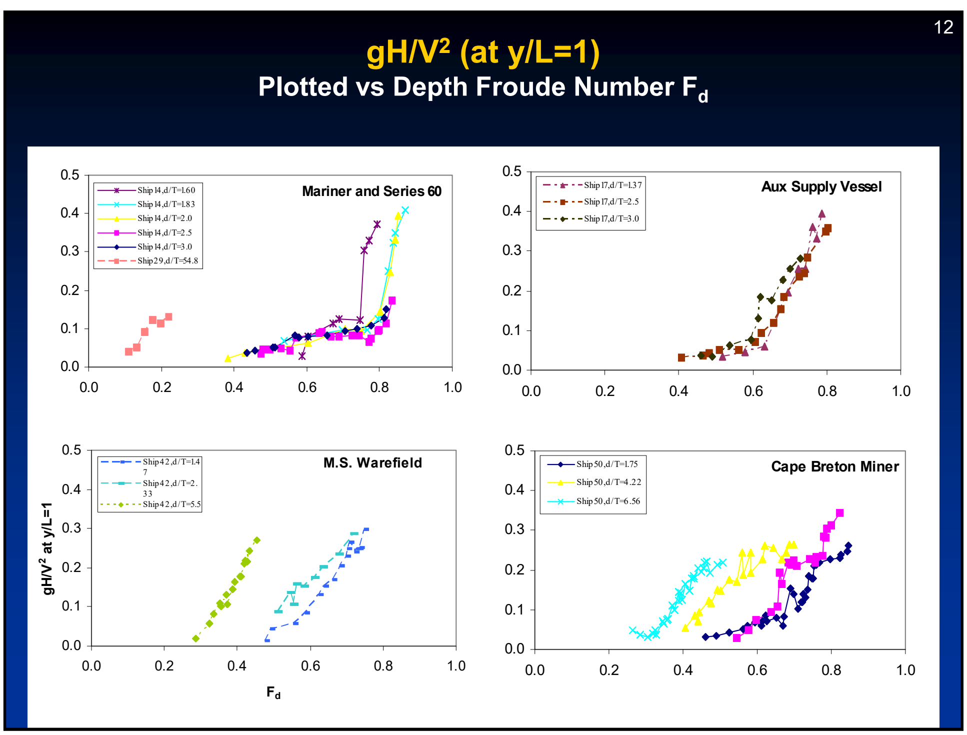
gH/V² (at y/L=1)
Plotted vs Length Froude Number F_L
Mariner and Series 60
Aux Supply Vessel
M.S. Warefield
Cape Breton Miner
gH/V² at y/L=1
F_L


12
gH/V² (at y/L=1)
Plotted vs Depth Froude Number F_d
Mariner and Series 60
Aux Supply Vessel
M.S. Warefield
Cape Breton Miner
gH/V² at y/L=1
F_d

Define Modified Froude Number F*

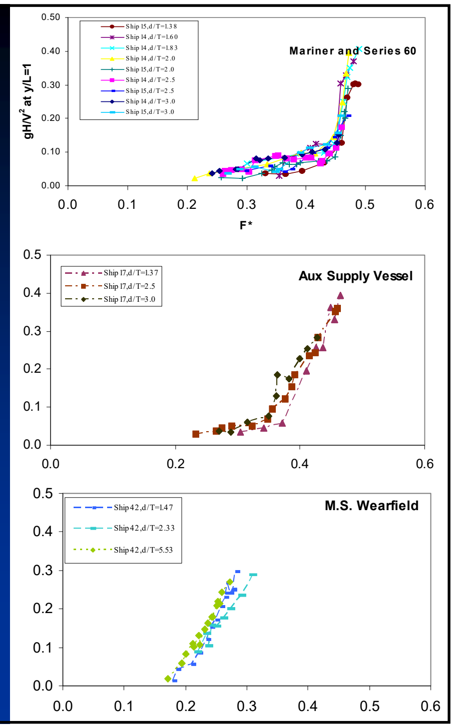
An empirical "Froude number" seems to collapse data from a given ship:

$$F_* = F_L \exp\left(\alpha \frac{D}{d}\right)$$

Single empirical coefficient α is dependent on ship hull form

α large for slender hulls

α small for blocky hulls



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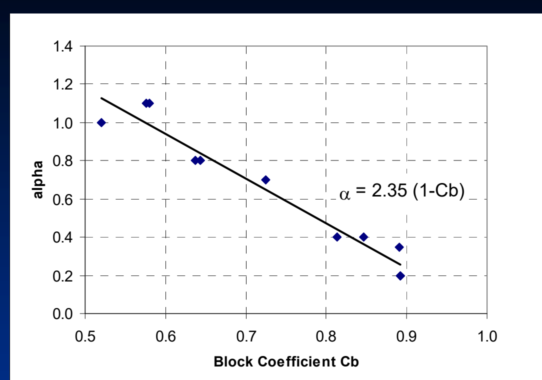
Variation of α with Hull Form

- Investigated dependence of α on hull form
- Seems to depend mainly on Block Coefficient

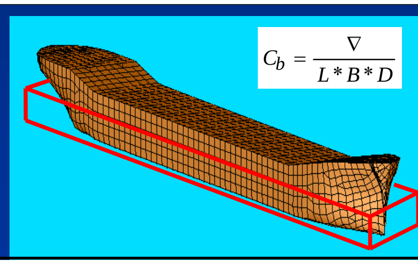
$$F_* = F_L \exp\left(\alpha \frac{D}{d}\right)$$

with

$$\alpha = 2.35\left(1 - C_b\right)$$



- General trends:
  - Streamlined hulls have α of 1 or more
  - Blunt hulls have α of 0.2 to 0.4



$$C_b = \frac{\nabla}{L * B * D}$$

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Search for Functional Relationship

between gH/V^2 and F_*

- Data for a given ship shows gH/V^2 increases with F_*
  - No waves measured for F_* below 0.1
  - Data shows quadratic or higher order relationship
  - Distinct variations observed as function of hull form
- No simple mathematical function seems to ideally describe data
- Preliminary work uses quadratic expression in the form

$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2$$

β varies with hull form and found by best fit of data for each ship

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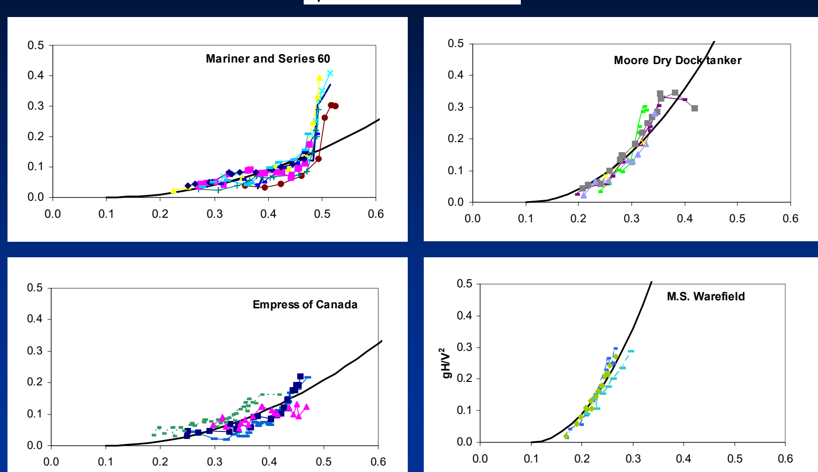
Results of gH/V^2 (at y/L=1)

Plotted vs Modified Froude Number F_* with empirical curve fit

$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2$$



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Results of gH/V^2 (at y/L=1)

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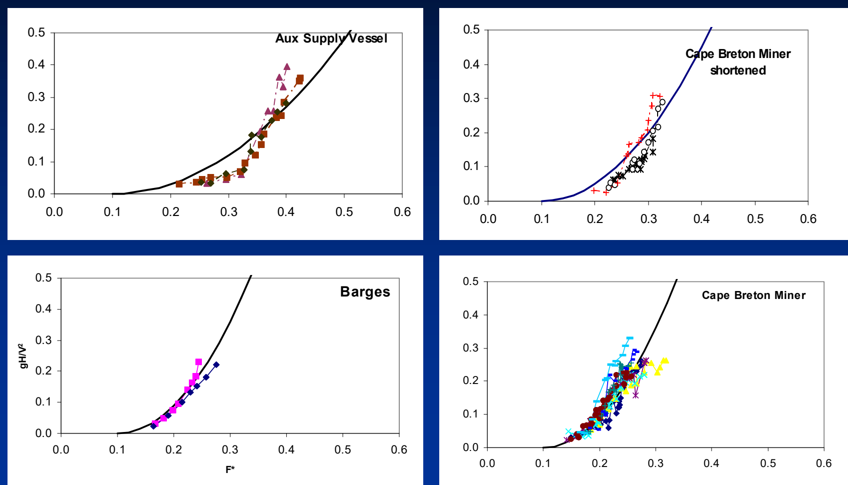

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Coefficient β seems to Vary with Entrance Length, Le

- Defined as length from bow to start of parallel middle-body
- Importance noted by Saunders (1957)
- Used in some other predictive models (Gates and Herbich, 1975)

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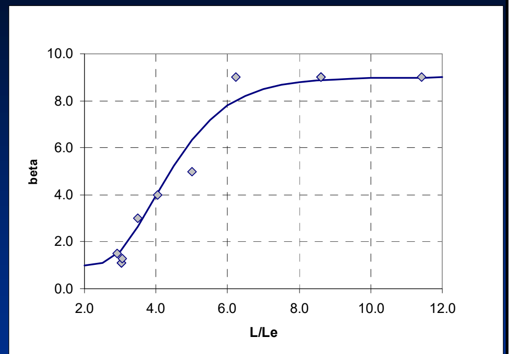
Variation of β with Hull Form

β correlated to entrance length

- Best correlation was based on L/Le ratio
  - Streamlined ships have β of 1 to 2
  - Blunt hulls have β up to 9
- Tentative relationship:

$$\beta = 1 + 8 * \tanh^3\left(0.45\left(\frac{L}{L_e} - 2\right)\right)$$



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Evaluation of Wave Height Models

Model developed in present study compared to 1200+ data points

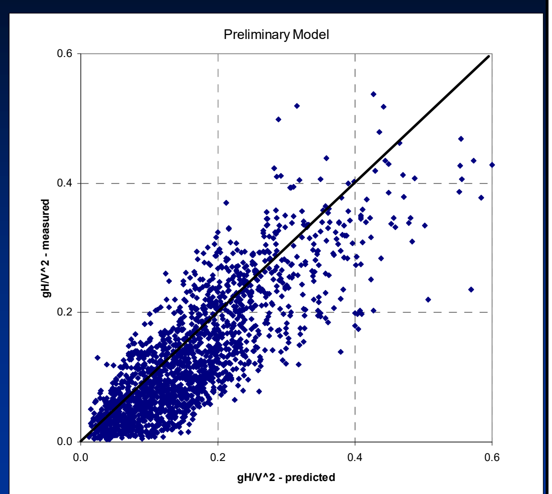
$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2\left(\frac{y}{L}\right)^{-1/3}$$

where

$$F_* = F_L \exp\left(\alpha\frac{T}{d}\right)$$

$$\alpha = 2.5(1 - C_b)$$

$$\beta = 1 + 8\tanh^3\left(0.45\left(\frac{L}{Le} - 2\right)\right)$$



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Evaluation of Wave Height Models

- Sorensen & Weggel (1984) and Weggel & Sorensen (1986)

$$H^* = \alpha\left(Y^*\right)^n$$

where

$$\log\alpha = a + b\log d^* + c(\log d^*)^2$$

with

$$a = -0.6F_d^{-1} \quad b = 0.75F_d^{-0.125} \quad c = 2.653F_d - 1.95$$

and

$$n = \beta\left(d^*\right)^\delta$$

with

$$\beta = -0.225\,\mathrm{F}_d^{-0.699} \quad \text{for} \quad 0.2 < F_d < 0.55$$

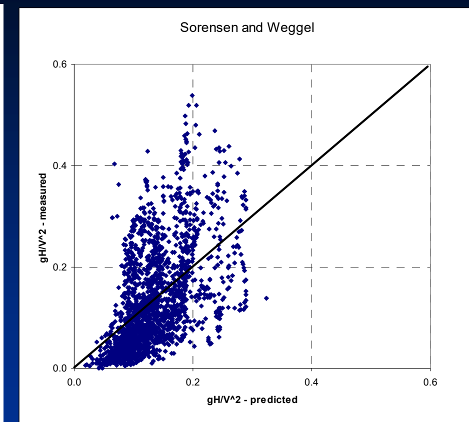
$$= -0.342 \quad \text{for} \quad 0.5 < F_d < 0.80$$

$$\delta = -0.118\,\mathrm{F}_d^{-0.356} \quad \text{for} \quad 0.2 < F_d < 0.55$$

$$= -0.146 \quad \text{for} \quad 0.5 < F_d < 0.80$$

and

$$H^* = \frac{H}{\nabla^{0.33}} \quad Y^* = \frac{Y}{\nabla^{0.33}} \quad d^* = \frac{d}{\nabla^{0.33}}$$



- A little complicated and removed from the physics
- Not dependent on hull form

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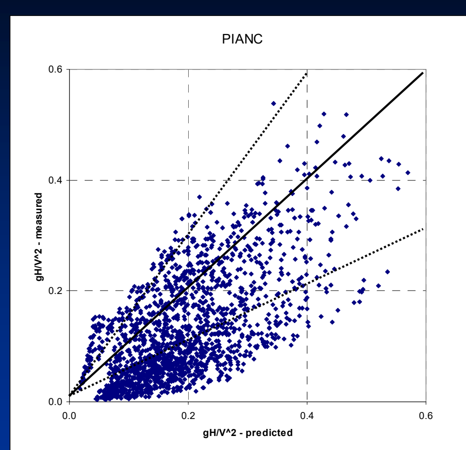
Evaluation of Wave Height Models

- PIANC (1987)
  - Based on work at Delft by Blaauw et al (1984) for ships in shallow confined canals

$$\frac{gH}{V^2} = F_d^2\left(\frac{y - B/2}{d}\right)^{-1/3}$$



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Ship Waves Trials
19 April 2005
Severn River (Chesapeake Bay)

Wave gage frame being deployed from YP686

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Wave gage deployed

26

YP686 at 10 knots

27

YP686 approaching wave gage
(gage located 100 ft off sailing line)

28

YP686 passing wave gage
(gage located 50 ft off sailing line)

29

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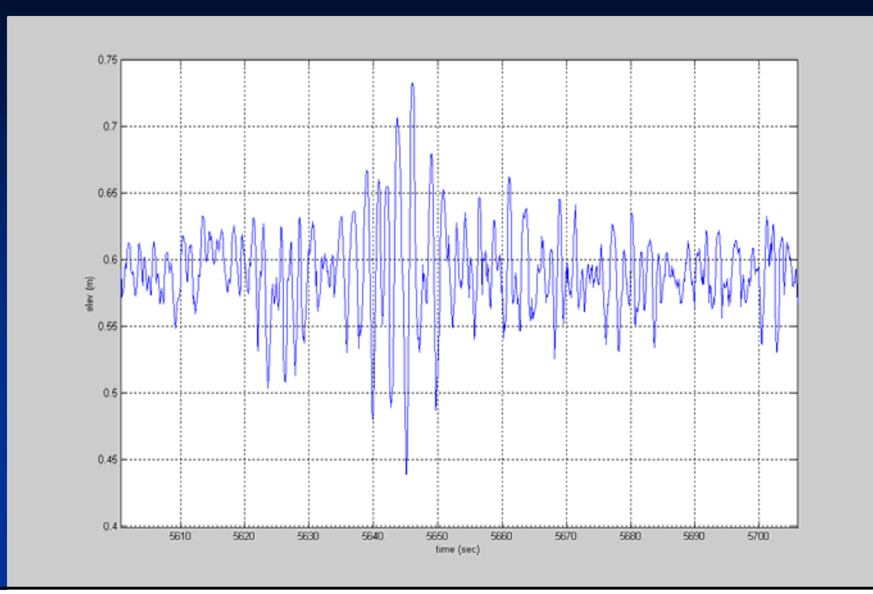
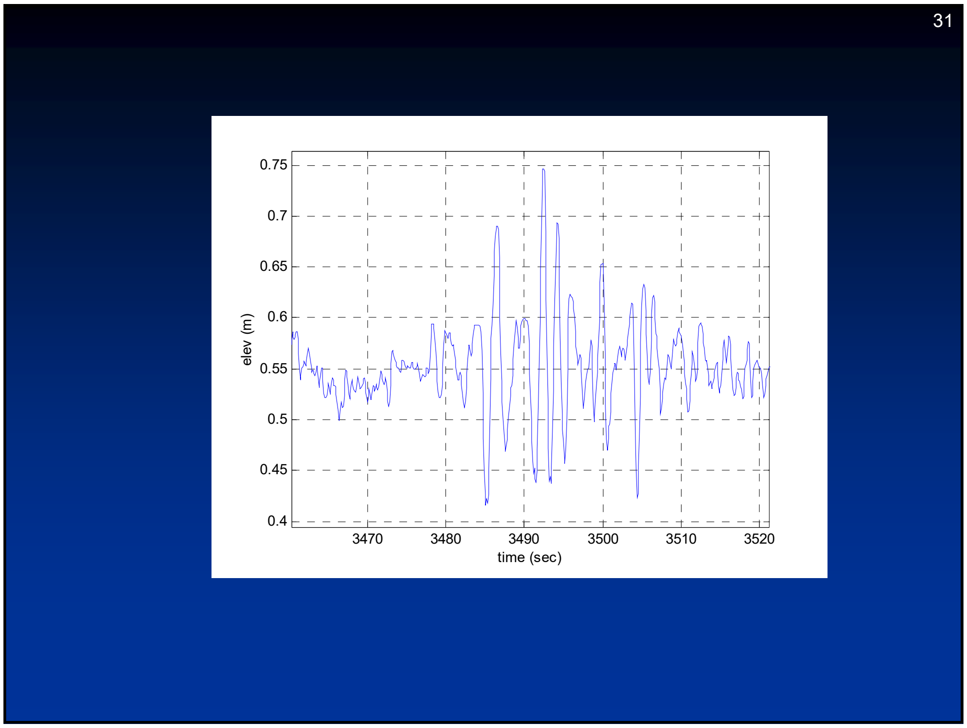
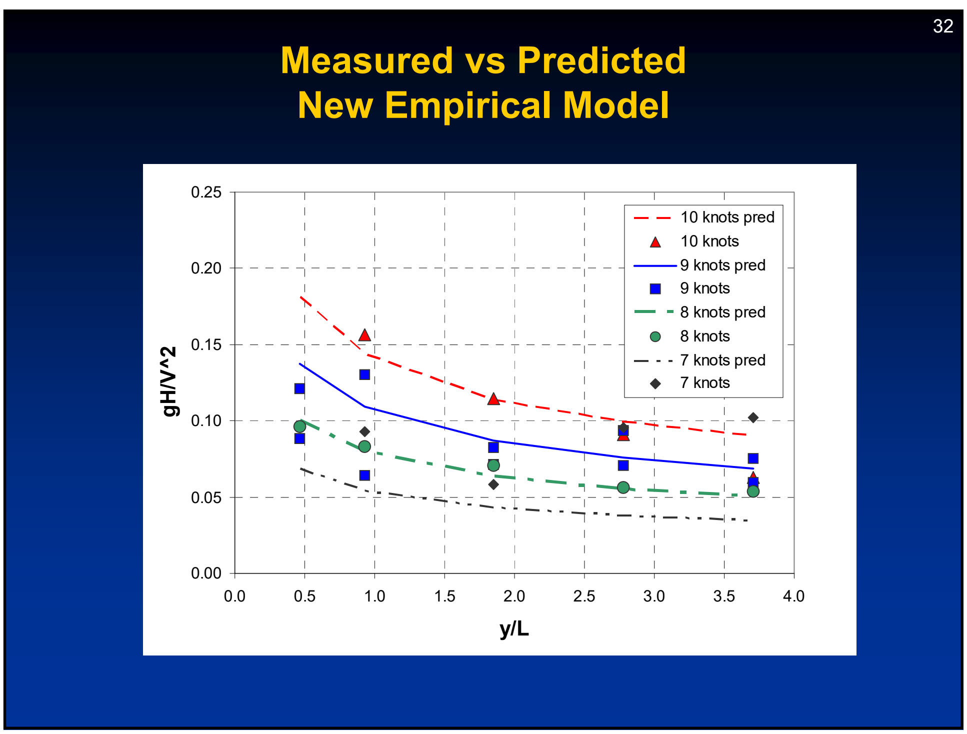
Sample data showing background wind waves and ship-generated waves




31
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
elev (m)
3470
3480
3490
3500
3510
3520
time (sec)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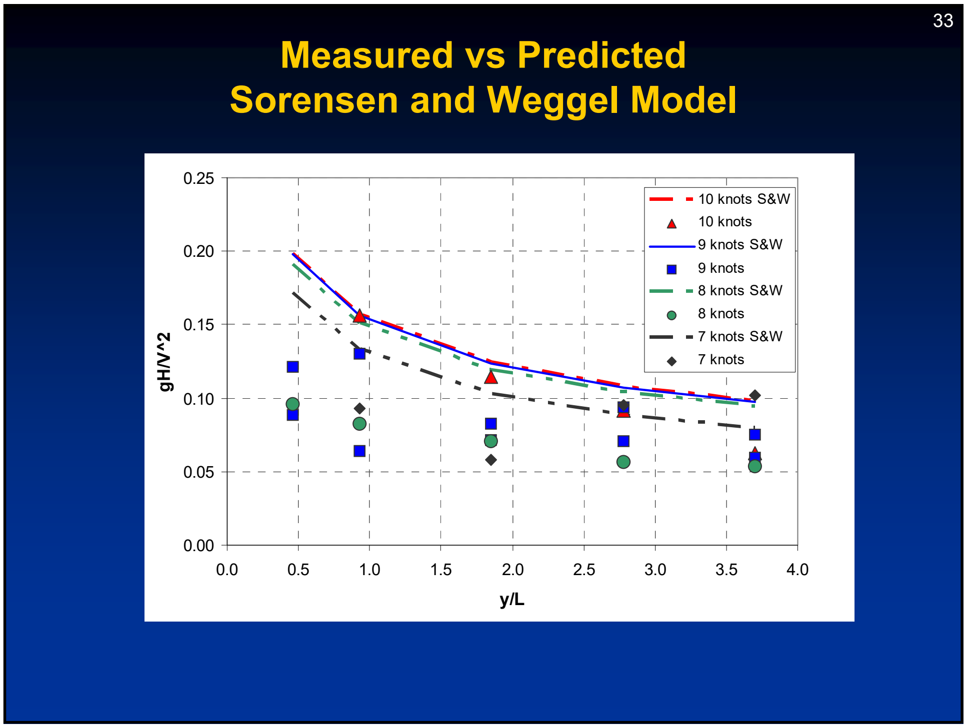
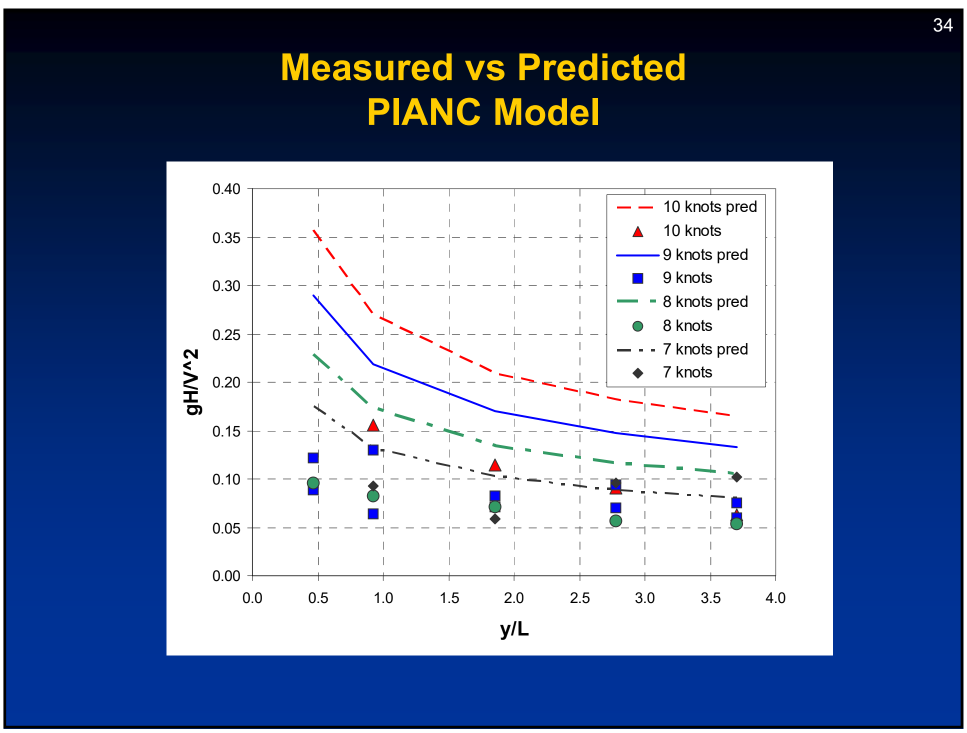
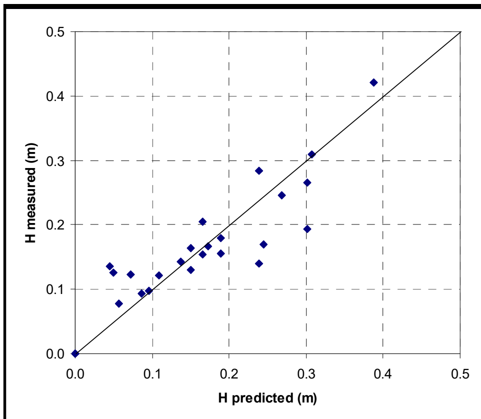
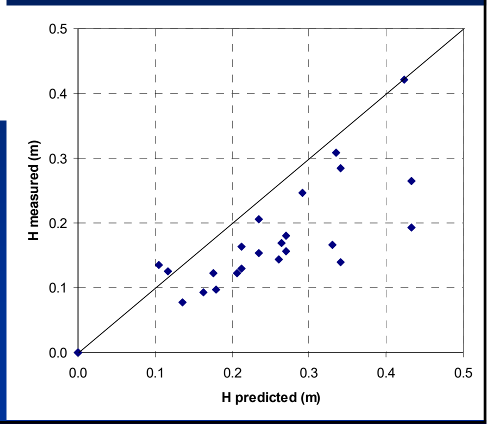
Measured vs Predicted
New Empirical Model
0.25
0.20
0.15
0.10
0.05
0.00
gH/V^2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
y/L
10 knots pred
10 knots
9 knots pred
9 knots
8 knots pred
8 knots
7 knots pred
7 knots


33
Measured vs Predicted
Sorensen and Weggel Model
gH/V^2
y/L
10 knots S&W
10 knots
9 knots S&W
9 knots
8 knots S&W
8 knots
7 knots S&W
7 knots


34
Measured vs Predicted
PIANC Model
gH/V^2
y/L
10 knots pred
10 knots
9 knots pred
9 knots
8 knots pred
8 knots
7 knots pred
7 knots

35





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Summary and Conclusions
Ship-Generated waves

- New model gives improved predictions
  - exp(αT/d) term "unifies" data collected in various water depths
- Model can be further improved
  - $(y/L)^{-1/3}$ can be optimized
    - Exponent may depend on hull form
  - $(F_*-0.1)^2$ can be optimized
    - Higher power needed for some hull forms
  - Coefficients α and β can be improved with data from more ships
- Need data in shallow water
  - Lab data for very shallow water T/d <1.3
  - Field data

$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2 \left(\frac{y}{L}\right)^{-1/3}$$

where

$$F_* = F_L \exp\left(\alpha \frac{T}{d}\right)$$

$$\alpha = 2.35(1 - C_b)$$

$$\beta = 1 + 8\tanh^3\left(0.45\left(\frac{L}{Le} - 2\right)\right)$$


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