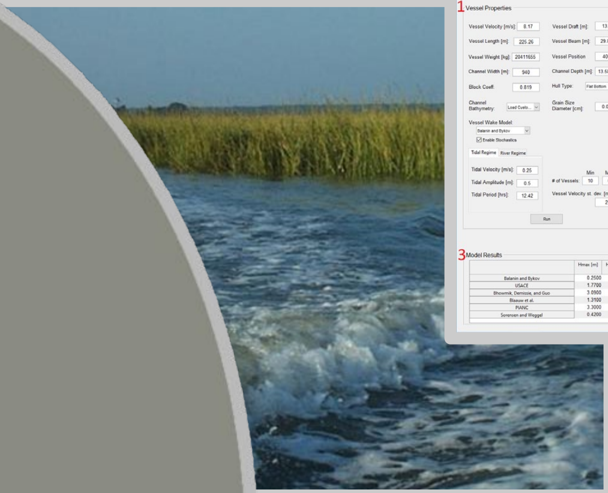
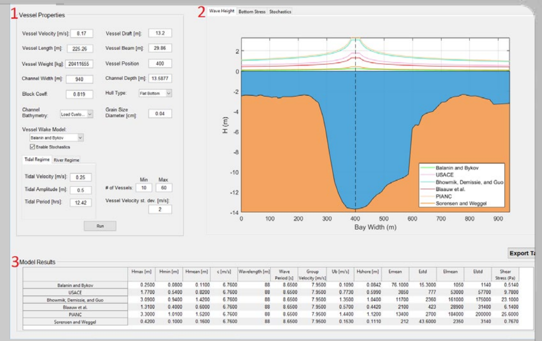
U.S.ARMY

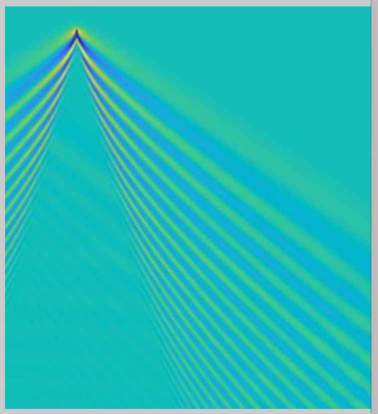
CIRP
Mission Support · Technology Transfer · Research & Development

EMPIRICAL & IDEALIZED NUMERICAL MODELING OF VESSEL WAKE

Richard Styles, Doug Krafft,
Cody Johnson







Kathy Griffin
HQ Navigation Business Line Manager

Eddie Wiggins
Technical Director

US Army Corps of Engineers

CHL COASTAL & HYDRAULICS LABORATORY

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER
DISCOVER | DEVELOP | DELIVER

Vessel Wake Prediction Tool

Input

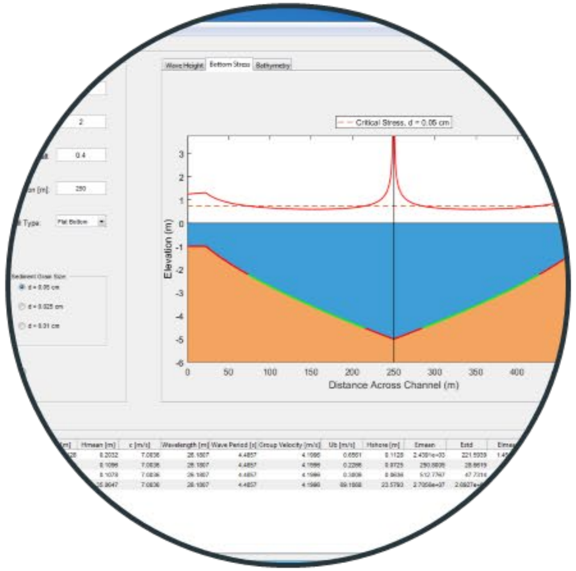
Model Calibration

- Flow measurements
- Channel geometry
- Bank characteristics (e.g., mud, sand, oysters)
- Sediment type & distribution

Vessel Information

- Speed
- Draft, Beam, Length
- Traffic Density

Output



Wave height distribution, energy flux due to commercial & recreational vessel traffic.

Primary Approach

Past Work Summary

- Construct GUI based on available model formulations
- Develop capability to evaluate vessel wake effects given potential change in vessel activity
- Utilize higher fidelity models & data to reduce uncertainty

Screen Shot of Primary Interface

Boat Wake Height_v3

File Edit View Insert Tools Desktop Window Help

Vessel Properties

Vessel Velocity [m/s]: 6.17
Water Depth [m]: 2.3727
Vessel Length [m]: 225.26
Vessel Beam [m]: 29.86
Vessel Weight [kg]: 20411655
Vessel Draft [m]: 10.2
Channel Width [m]: 940
Vessel Position [m]: 400
Block Coeff: 0.848
Hull Type: Flat Bottom
Channel Bathymetry: Load Custo...
Grain Size Diameter [cm]: 0.04

Vessel Wake Model: Balanin and Bykov

Enable Stochastics

Tidal Regime | River Regime

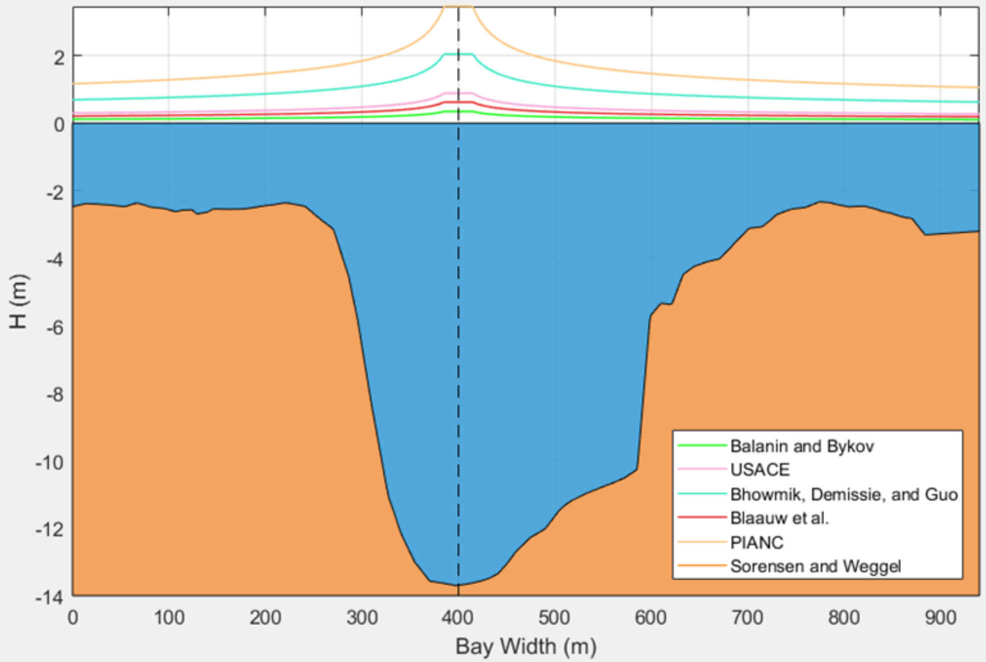
Tidal Velocity [m/s]: 0.25
Tidal Amplitude [m]: 0.5
Tidal Period [hrs]: 12.42

\# of Vessels: Min 10, Max 60

Vessel Velocity st. dev. [m/s]: 2

Run

Wave Height | Bottom Stress | Stochastics



Export Table

Model Results

	Hmax [m]	Hmin [m]	Hmean [m]	c [m/s]	Wavelength [m]	Wave Period [s]	Group Velocity [m/s]	Ub [m/s]	Hshore [m]	Emean	Estd	Elmean	Elstd	Shear Stress (Pa)
Balanin and Bykov	0.3500	0.1100	0.1600	4.8200	54.7000	6.1800	5.7900	0.1450	0.1170	148	29.9000	1150	1090	0.9380
USACE	0.8900	0.2700	0.4100	4.8200	54.7000	6.1800	5.7900	0.3700	0.3000	966	195	7470	7080	3.7600
Bhowmik, Demissie, and Guo	2.0500	0.6300	0.9400	4.8200	54.7000	6.1800	5.7900	0.8540	0.6920	5150	1040	39800	37700	13.3000
Blaauw et al.	0.6200	0.1900	0.2900	4.8200	54.7000	6.1800	5.7900	0.2600	0.2110	477	96.1000	3690	3490	2.2200
PIANC	3.4600	1.0600	1.6000	4.8200	54.7000	6.1800	5.7900	1.4400	1.1700	14700	2960	113000	107000	29.8000
Sorensen and Weggel	NaN	NaN	NaN	4.8200	54.7000	6.1800	5.7900	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Vessel Stochastics

Boat Wake Height_v3

File Edit View Insert Tools Desktop Window Help

Vessel Properties

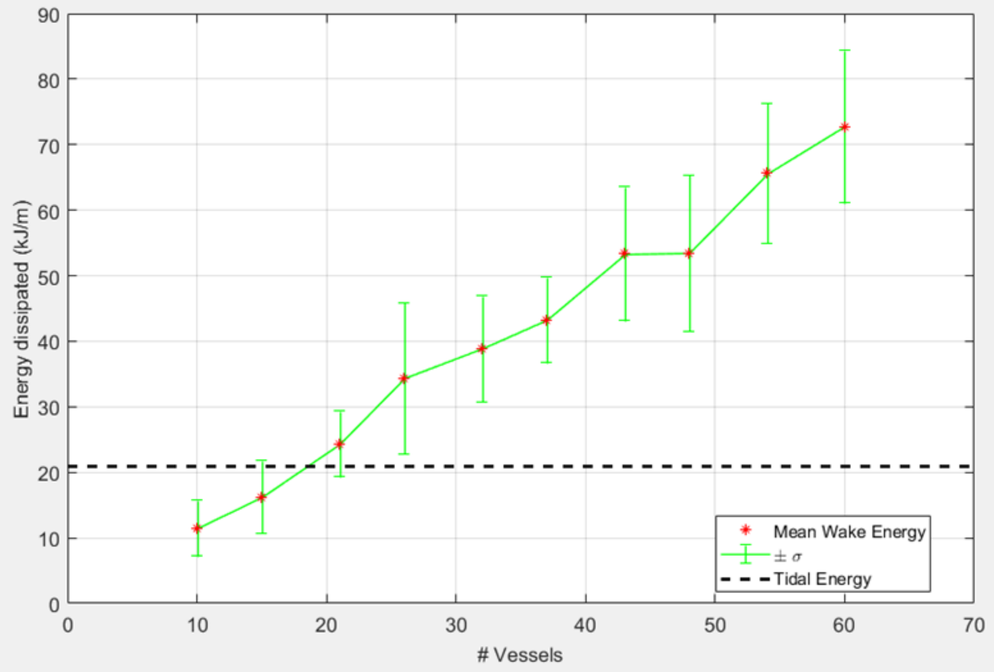
Vessel Velocity [m/s]: 6.17
Water Depth [m]: 2.3727
Vessel Length [m]: 225.26
Vessel Beam [m]: 29.86
Vessel Weight [kg]: 20411655
Vessel Draft [m]: 10.2
Channel Width [m]: 940
Vessel Position [m]: 400
Block Coeff: 0.848
Hull Type: Flat Bottom
Channel Bathymetry: Load Custo...
Grain Size Diameter [cm]: 0.04
Vessel Wake Model: Balanin and Bykov
☑ Enable Stochastics

Tidal Regime | River Regime

Tidal Velocity [m/s]: 0.25
Tidal Amplitude [m]: 0.5
Tidal Period [hrs]: 12.42
# of Vessels: Min 10, Max 60
Vessel Velocity st. dev. [m/s]: 2

Run

Wave Height | Bottom Stress | Stochastics



Export Table

Model Results

	Hmax [m]	Hmin [m]	Hmean [m]	c [m/s]	Wavelength [m]	Wave Period [s]	Group Velocity [m/s]	Ub [m/s]	Hshore [m]	Emean	Estd	Elmean	Elstd	Shear Stress (Pa)
Balanin and Bykov	0.3500	0.1100	0.1600	4.8200	54.7000	6.1800	5.7900	0.1450	0.1170	148	29.9000	1150	1090	0.9380
USACE	0.8900	0.2700	0.4100	4.8200	54.7000	6.1800	5.7900	0.3700	0.3000	966	195	7470	7080	3.7600
Bhowmik, Demissie, and Guo	2.0500	0.6300	0.9400	4.8200	54.7000	6.1800	5.7900	0.8540	0.6920	5150	1040	39800	37700	13.3000
Blaauw et al.	0.6200	0.1900	0.2900	4.8200	54.7000	6.1800	5.7900	0.2600	0.2110	477	96.1000	3690	3490	2.2200
PIANC	3.4600	1.0600	1.6000	4.8200	54.7000	6.1800	5.7900	1.4400	1.1700	14700	2960	113000	107000	29.8000
Sorensen and Weggel	NaN	NaN	NaN	4.8200	54.7000	6.1800	5.7900	NaN	NaN	NaN	NaN	NaN	NaN	NaN

COASTAL & HYDRAULICS LABORATORY

Export Results to Microsoft Excel

demo_export.xlsx - Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Vessel Velocity [m/s]	6.17	Water Depth [m]	2.3727															
2	Vessel Length [m]	225.26	Vessel Beam [m]	29.86															
3	Vessel Weight [kg]	20411655	Vessel Draft [m]	10.2															
4	Channel Width [m]	940	Vessel Position	400															
5	Block Coeff	0.848	Hull Type	Flat Bottom															
6	Channel Bathymetry	C:\Users\rdchlmah\	Grain Size Diameter [cm]	0.04															
7																			
8	Model Statistics																		
9		Hmax [m]	Hmin [m]	Hmean [m]	c [m/s]	Wavelength [m]	Wave Period [s]	Group Velocity [m/s]	Ub [m/s]	Hshore [m	Emean	Estd	Elmean	Elstd	Shear Stress (Pa)				
10	Balanin and Bykov	0.35	0.11	0.16	4.82	54.7	6.18	5.79	0.145	0.117	148	29.9	1150	1090	0.938				
11	USACE	0.89	0.27	0.41	4.82	54.7	6.18	5.79	0.37	0.3	966	195	7470	7080	3.76				
12	Bhowmik, Demissie, and Guo	2.05	0.63	0.94	4.82	54.7	6.18	5.79	0.854	0.692	5150	1040	39800	37700	13.3				
13	Blaauw et al.	0.62	0.19	0.29	4.82	54.7	6.18	5.79	0.26	0.211	477	96.1	3690	3490	2.22				
14	PIANC	3.46	1.06	1.6	4.82	54.7	6.18	5.79	1.44	1.17	14700	2960	113000	107000	29.8				
15	Sorensen and Weggel																		
16																			
17	Model Wave Heights																		
18	x (m)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
19	Depth (m)	2.462680749	2.462680749	2.456719659	2.450499	2.444277882	2.438056932	2.431835982	2.425615	2.419394	2.413173	2.406952	2.400731	2.39451	2.388289	2.382068	2.382502	2.384078	2.3856
20	Balanin and Bykov	0.117485723	0.11758281	0.117680221	0.117778	0.117876024	0.117974419	0.118073146	0.118172	0.118272	0.118371	0.118471	0.118572	0.118673	0.118774	0.118875	0.118977	0.119079	0.1191
21	USACE	0.29993381	0.300181668	0.300430353	0.30068	0.300930225	0.301181423	0.301433467	0.301686	0.30194	0.302195	0.30245	0.302707	0.302964	0.303222	0.303481	0.303741	0.304002	0.3042
22	Bhowmik, Demissie, and Guo	0.692322325	0.692894442	0.69346847	0.694044	0.694622301	0.695202127	0.695783908	0.696368	0.696953	0.697541	0.698131	0.698723	0.699316	0.699912	0.70051	0.70111	0.701712	0.7023
23	Blaauw et al.	0.210652812	0.21082689	0.211001549	0.211177	0.211352625	0.211529049	0.211706067	0.211884	0.212062	0.212241	0.21242	0.2126	0.212781	0.212962	0.213144	0.213327	0.21351	0.2136
24	PIANC	1.168719117	1.169684916	1.17065394	1.171626	1.172601739	1.173580551	1.174562664	1.175548	1.176537	1.177529	1.178525	1.179523	1.180526	1.181532	1.182541	1.183554	1.18457	1.185
25	Sorensen and Weggel																		
26																			
27	Model Bottom Stress (N/m^2)	Critical Stress = 0.584 N/m^2																	
28	x (m)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
29	Depth (m)	2.462680749	2.462680749	2.456719659	2.450499	2.444277882	2.438056932	2.431835982	2.425615	2.419394	2.413173	2.406952	2.400731	2.39451	2.388289	2.382068	2.382502	2.384078	2.3856
30	Balanin and Bykov	0.938337836	0.939468027	0.94258445	0.945805	0.949044784	0.952302936	0.955579938	0.958876	0.962191	0.965526	0.96888	0.972253	0.975647	0.97906	0.982494	0.983567	0.984236	0.9849
31	USACE	3.755133537	3.759788021	3.772623078	3.785889	3.799233067	3.812654837	3.826155271	3.839735	3.853395	3.867135	3.880957	3.894861	3.908847	3.922917	3.937072	3.941496	3.944254	3.9470
32	Bhowmik, Demissie, and Guo	13.32744175	13.34427863	13.3907093	13.4387	13.4869791	13.53554081	13.58439005	13.63353	13.68296	13.73269	13.78271	13.83304	13.88366	13.93459	13.98583	14.00185	14.01184	14.021
33	Blaauw et al.	2.215971589	2.218692204	2.226194366	2.233948	2.241747492	2.249592023	2.257482339	2.265419	2.273402	2.281432	2.289509	2.297634	2.305808	2.314029	2.3223	2.324885	2.326497	2.3281
34	PIANC	29.80699803	29.84509334	29.95015091	30.05875	30.16799253	30.27788635	30.38843574	30.49965	30.61152	30.72407	30.8373	30.95121	31.06582	31.18111	31.29712	31.33337	31.35598	31.378
35	Sorensen and Weggel																		

Sheet1

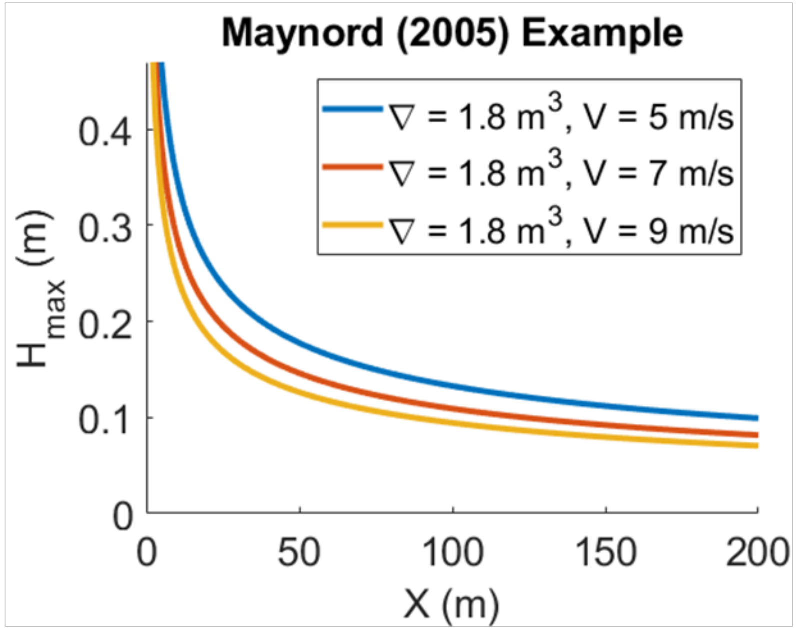
Empirical Recreational Vessel Wake Modeling

Maynord (2005) Wave Height from Planing and Semi-planing Small Boats

$$\frac{H_m}{W^{1/3}} = C_m F_w^{-0.58} \left(\frac{x}{W^{1/3}}\right)^{-0.42}$$

Where:

H_m	is predicted wake height
W	is displaced volume
x	is distance from the vessel centerline
C_m	is the vessel shape coefficient (suggested as 0.82 – 1)
F_w	is the displacement Froude number



Displacement Froude Number

$$F_w = \frac{V_s}{\sqrt{gW^{1/3}}}$$

Where:

V_s	is vessel speed

Note: data forming empirical model is not without substantial scatter

Idealized Numerical Modeling

FUNWAVE

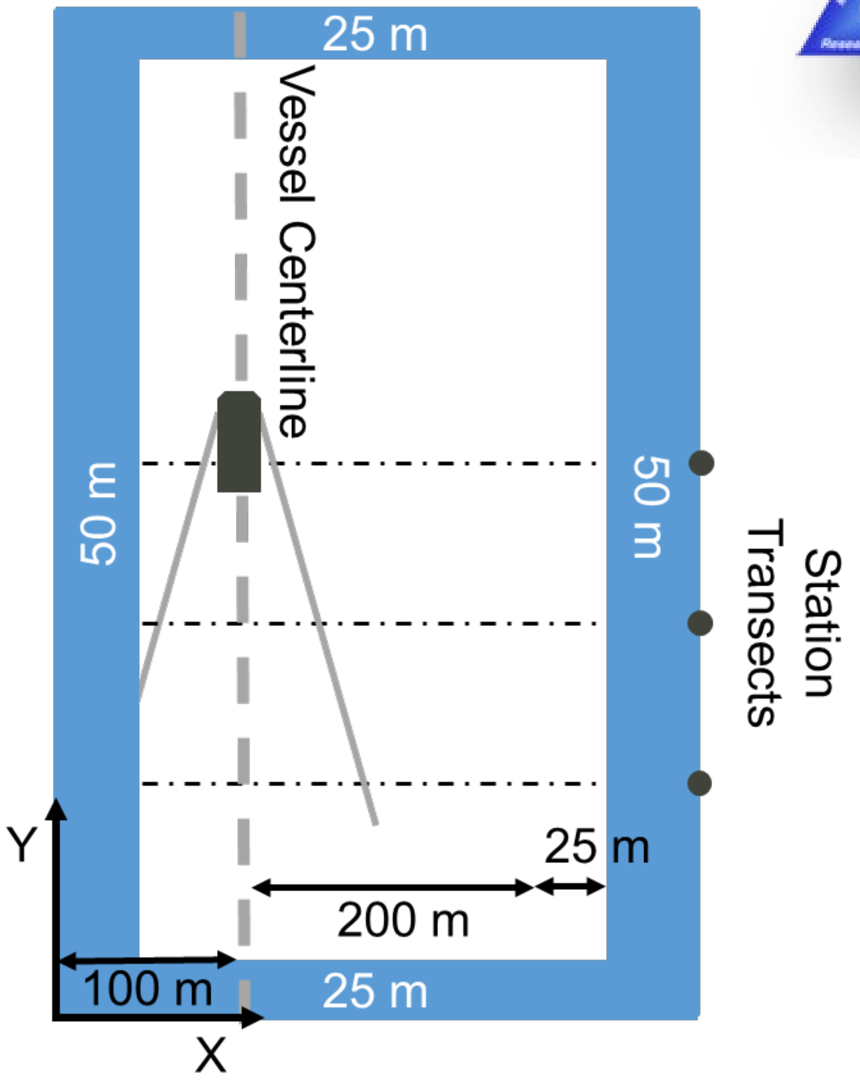
- Fully non-linear Boussinesq model (Shi et al. 2012)

https://fengyanshi.github.io/build/html/index.html

- Includes a ship-wake module
  - Validated against laboratory experiments (Gorlay, 2001) in Shi et al. (2018)

Idealized Simulations

- Simulating a single vessel, traveling through a flat domain
- Domain Size: 375 m x 1,110 m – 1,925 m
- Depth (Constant): 1.75 m
- Detailed output:
  - Stations along 3 transects



Intended Vessel Wake Numerical Modeling Regime

Intended Model Regime

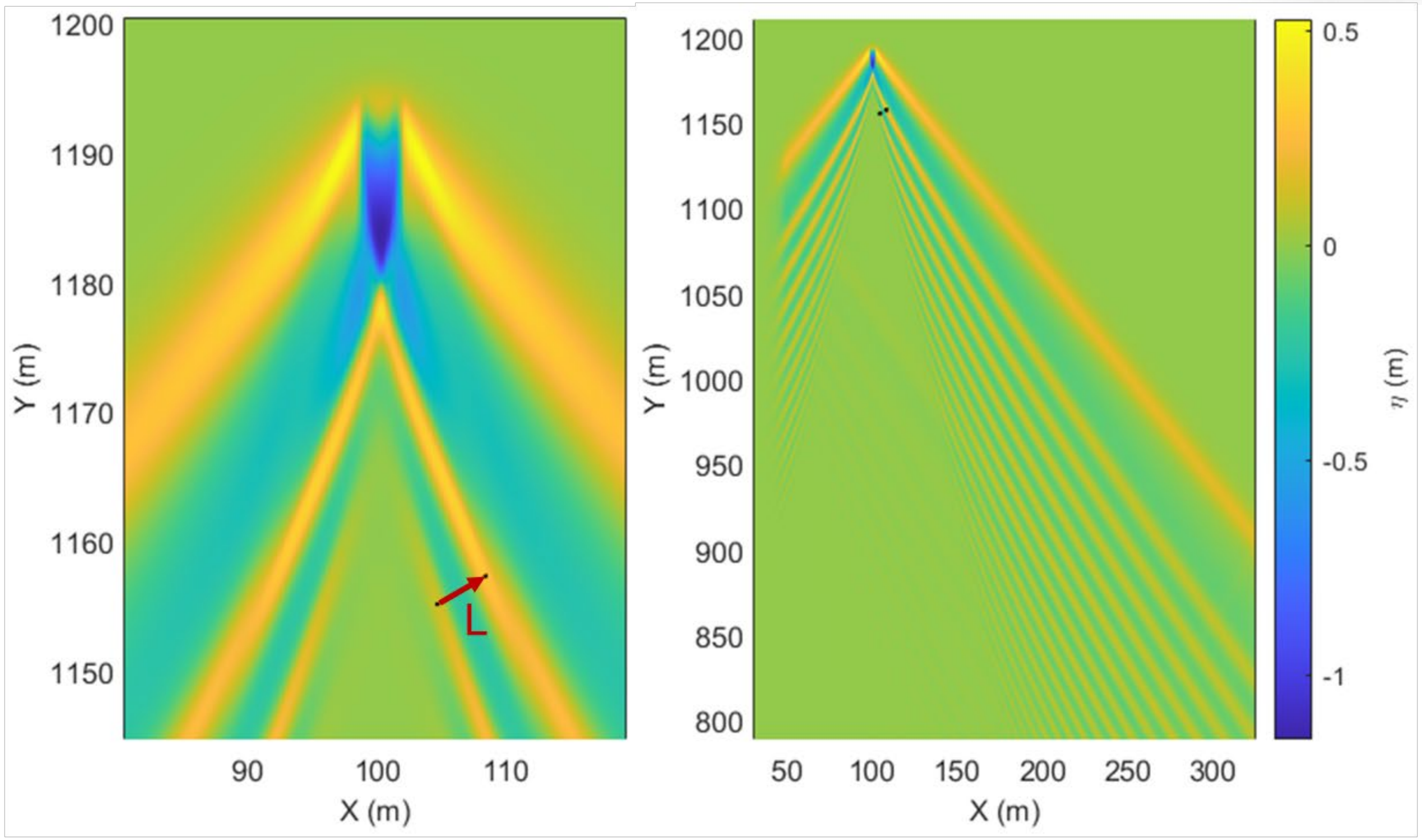
- Intermediate and shallow water waves

$$k \cdot h < \pi$$

$$h < \frac{L}{2}$$

Simulated Wake Length

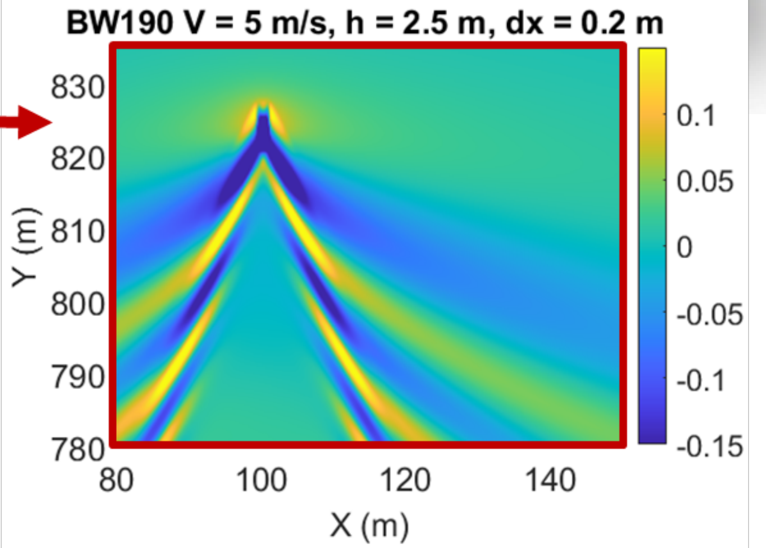
- Wake length estimated as the distance between peaks near the vessel
- Manual point selection (accuracy with 0.2 m cells)
- Issues encountered in simulations with $L/2 < h$

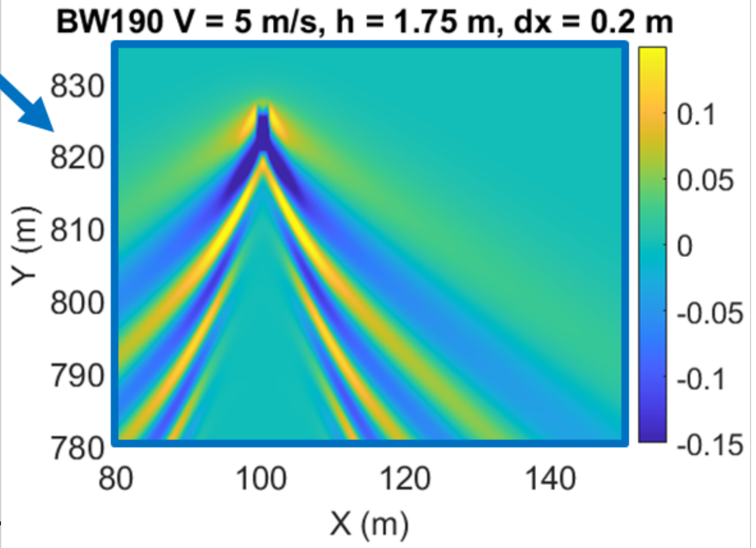


Test Simulations Relative to Intended Wake Regime

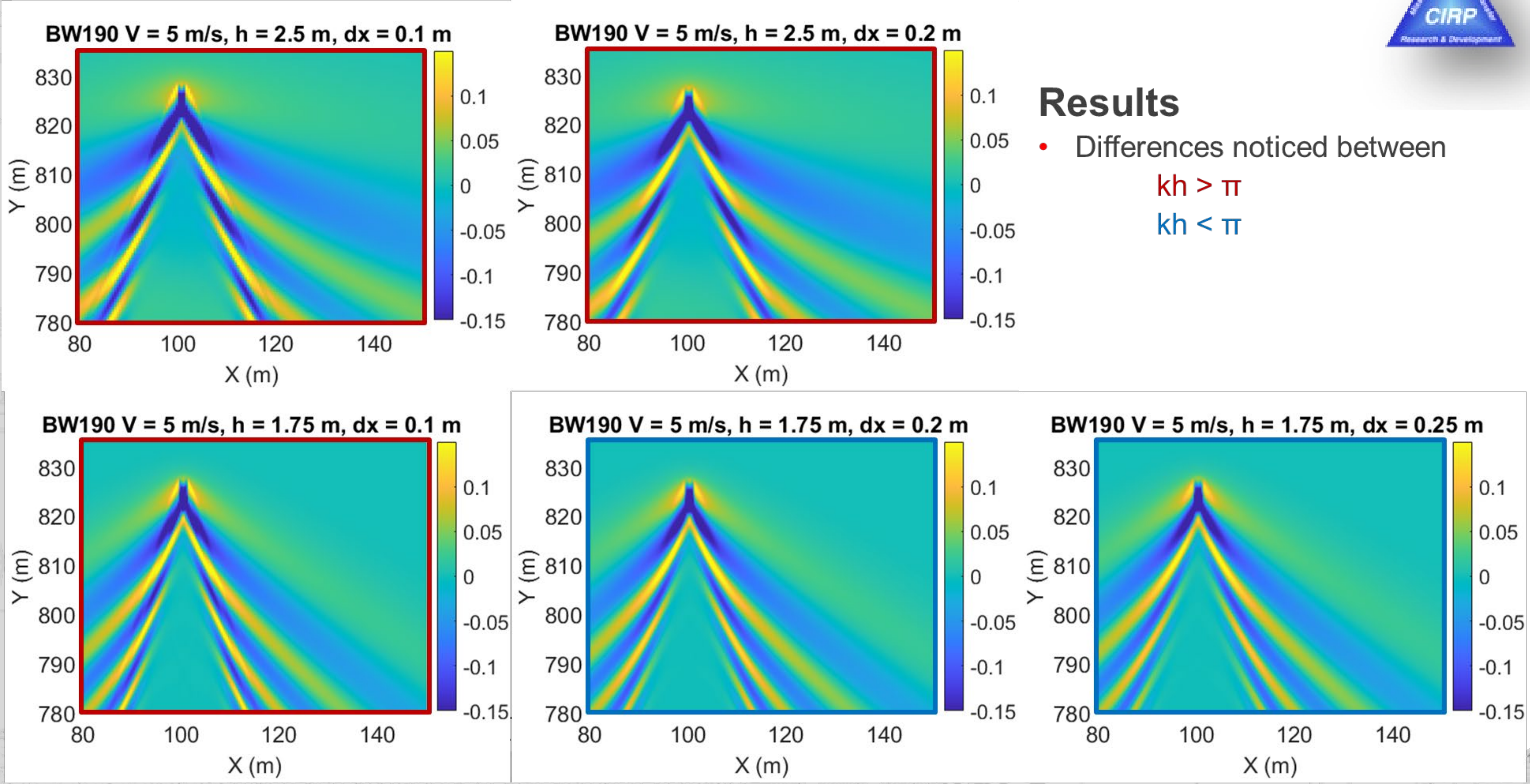
Vessel	Speed	Depth	Wake Length	kh/π
BW190	5 m/s	2.5 m	3.5 – 4.5 m	1.1 – 1.4
BW190	5 m/s	1.75 m	3.5 – 4.5 m	0.8 – 1
BW190	7 m/s	3.5 m	3.5 – 4.5 m	1.6 – 2
BW190	7 m/s	1.75 m	3.5 – 4.5 m	0.8 – 1

- Manual selection accuracy estimated as ~ ± 2 cells
- Changes in minimum wake length are less than method accuracy
- No noticeable wake length changes with tested depths & speeds
- Minimum wake lengths are sometimes greater than minima for intended regime (kh<π)
- Maynord (2005) model appears to be from scenarios in which kh > π for the minimum wake length (h > 3.5 m).





Wake Length and Depth Impact *(2 Ton Vessel, 5 m/s)*

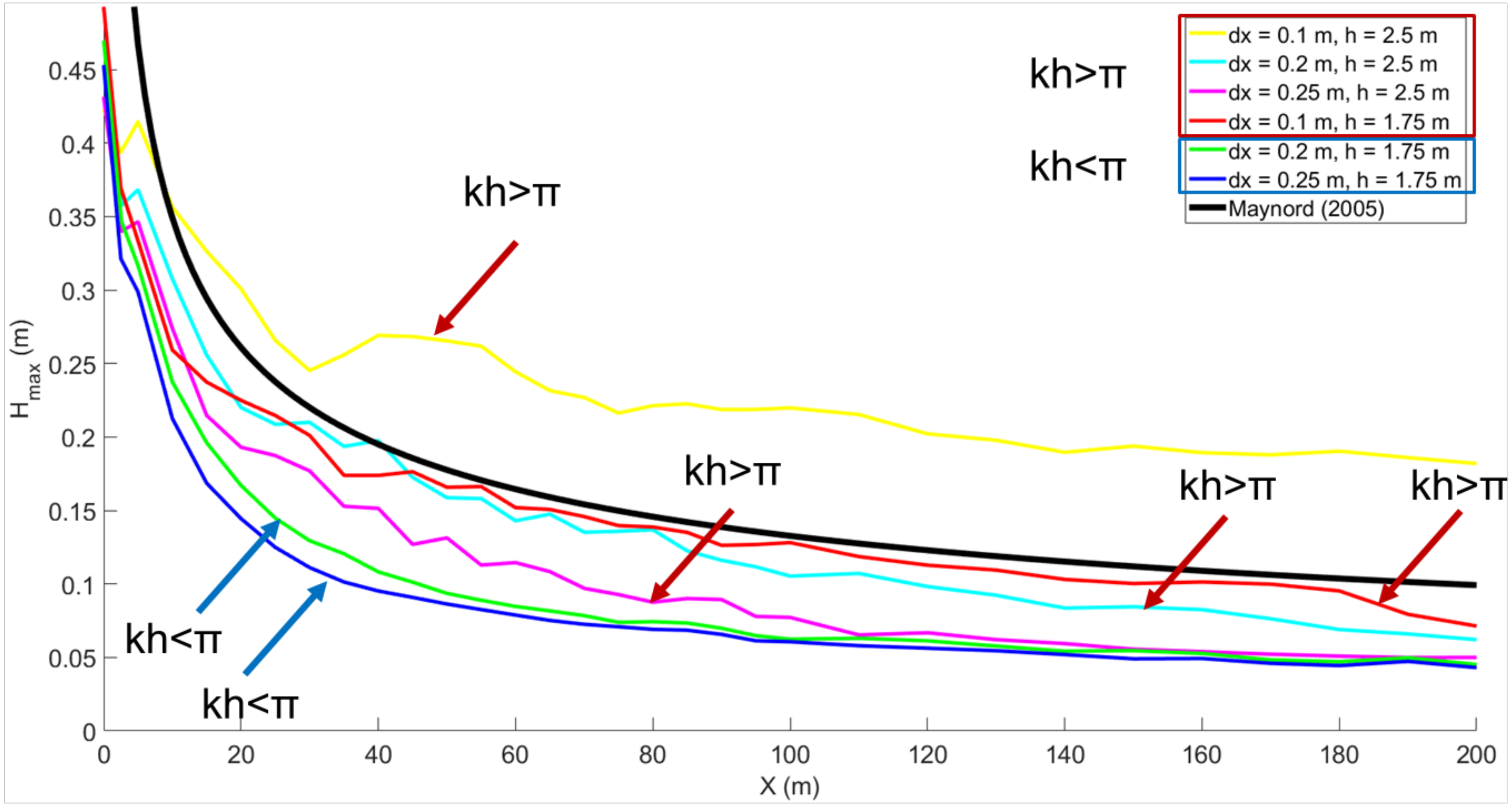


Results

- Differences noticed between
  - $kh > \pi$
  - $kh < \pi$

Idealized Numerical Model Solutions (Depth and Resolution Impact)

2 Ton Vessel, 5 m/s



Results

- H_{max} vary substantially where kh > π
- Results where kh < π appear to be reasonable, but H_{max} in these scenarios may be limited by depth.
- Concerns on adequately resolving wakes remain

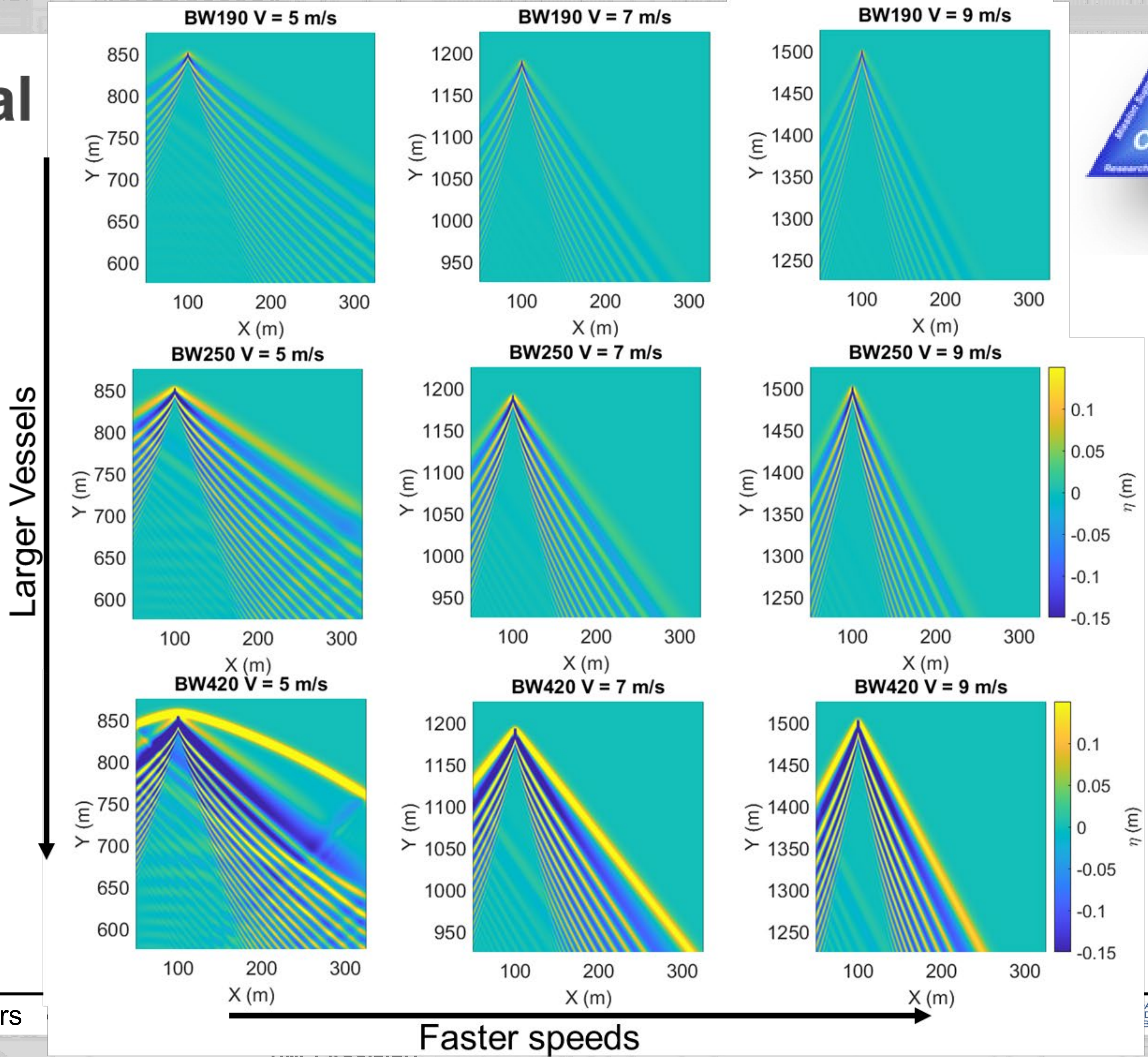
Idealized Numerical Model Test Matrix

Vessel

- BW190: 2 Ton
- BW250: 6 Ton
- BW420: 23 Ton

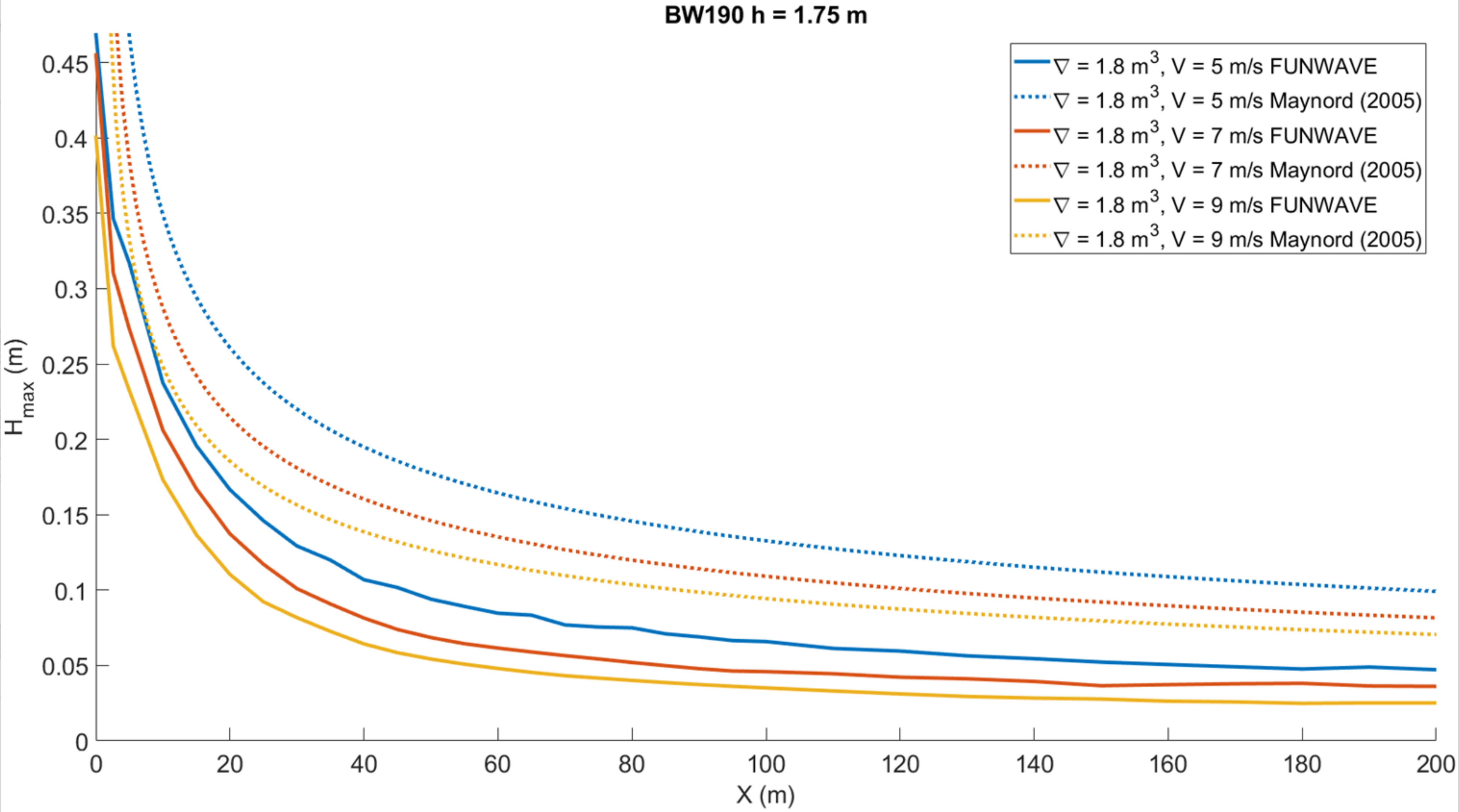
Speed

- Completed: 5 m/s (10 knots), 7 m/s (14 knots), 9 m/s (18 knots)
- Larger vessels cause substantial reflection.
  - Particularly at slower speeds
  - Testing underway to reduce reflections



Empirical vs. Idealized Numerical Model Solutions

2 Ton Vessel

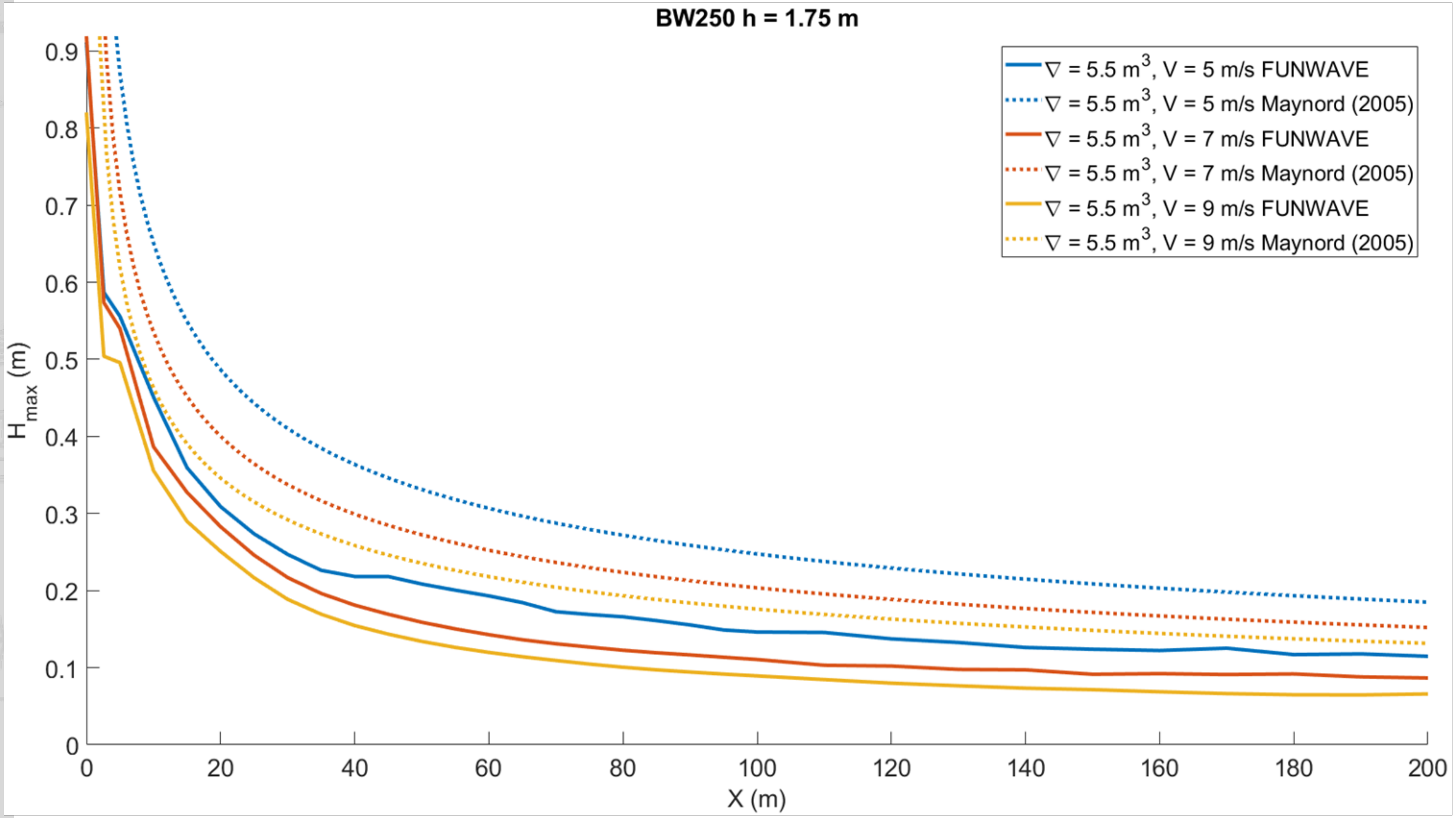


Results

- H_{max} decreases with vessel speed and distance, following findings of Maynord (2005)
- H_{max} ~ ½ of Maynord (2005) prediciton
- Maynord (2005) data collected in > 3.5 m depth
  - Depth limited solution?

Empirical vs. Idealized Numerical Model Solutions

6 Ton Vessel

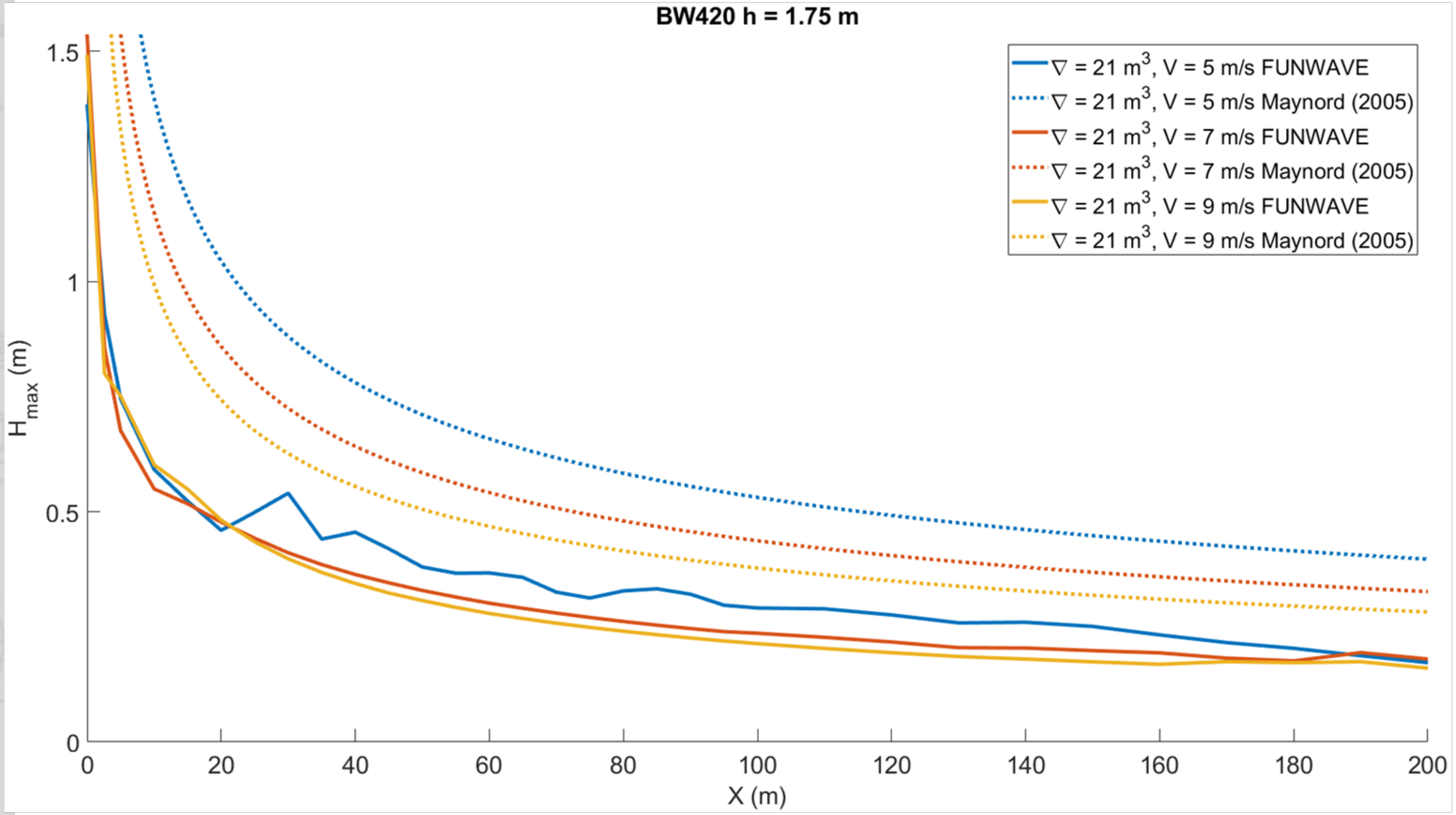


Results

- H_{max} decreases with vessel speed and distance.
- Less substantial H_{max} decrease with velocity than 2 ton vessel
- Maynord (2005) model developed with vessels lighter than 1.6 tons
- Reflection likely impacts results. Working on less reflective domains.

Empirical vs. Idealized Numerical Model Solutions

23 Ton Vessel



Results

- H_{max} does not decrease with speed
- Reflection likely impacts results. Working on less reflective domains.
- Maynord (2005) model developed with vessels lighter than 1.6 tons

Summary

Reasonable Recreational Vessel Wake Results

- Approaching reasonable solutions for relatively large recreational vessels in relatively shallow water

Persistent Issues

- Depth impact on solutions and the ability to assess the upper limit of vessel wake forcing
- Resolution dependence

Conclusions

Applicability for Scoping Level Recreational Vessel Wake Estimates

- Reliable solution matrix for a wide variety of conditions?
- Possibility remains for improved estimates of wake characteristics directly impacting edge erosion

Thank You!

Questions?