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Methodology for creating nonaxisymmetric WECs to screen mooring designs using a Morison Equation approach

Diana Bull and Paul Jacob

Oceans 2012

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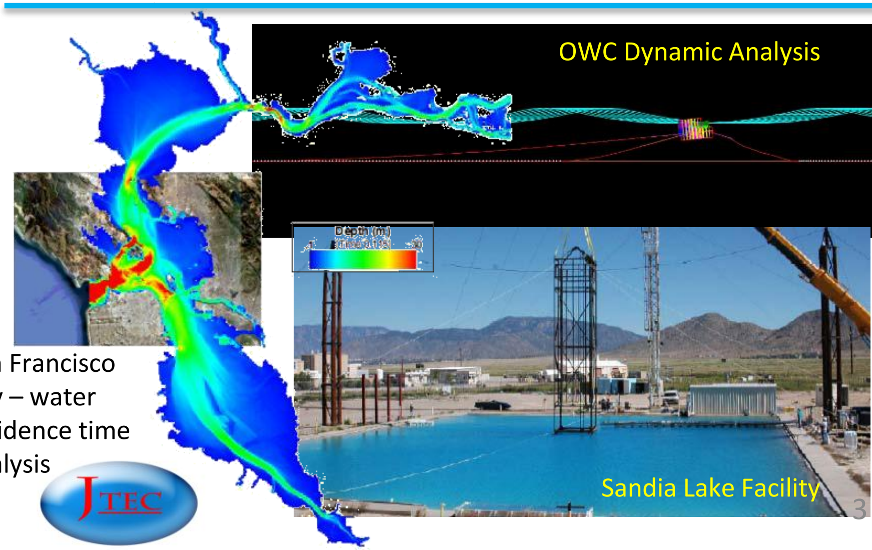
Sandia Water Power Overview

- **Technology Assessment: Reference Model Project**
  - Goal: obtain baseline Cost Of Energy (COE) estimates for a variety of Marine Hydro-Kinetic (MHK) devices.
- **Technology Development: Modeling Tools & Advanced Materials**
  - Modeling Tools: predict power performance of MHK devices
  - Advanced Materials: evaluate new corrosion resistant and antifouling material coatings
- **Market Acceleration: Environmental Impact**
  - SNL-EFDC: MHK –capable environmental circulation and array performance code
  - SNL-SWAN: tool to evaluate environmental effects of WEC arrays



San Francisco Bay – water residence time analysis

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Unique Capabilities

- SEAWOLF laboratory/field oscillatory-flow sediment transport testing
- Sandia Lake Facility – potential for large scale wave testing
- Ability to leverage defense spending on fundamental sciences: controls, hydrodynamics, aerodynamics, experimentation, etc.

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- Based in Houston Texas
- Joint US Agents for Orcina (OrcaFlex since 2009)
- Prior to 2009 Agent for Orcina with Third Party
- Participated in design of mooring systems for wave energy converters that are currently in service
- Other offshore experience in petroleum industry for deign of riser and mooring systems
- Licensed professional engineer in Texas and United Kingdom

Mooring System for WECs

- Costs are a significant portion of total installed cost
- Designed to survive the extreme environment at the deployment location
  - These environments drive the sizing of the mooring system components
- Large amplitude responses of the WEC must be predicted in these extreme environments.
  - Motions are typically beyond the limits of classic (radiation/diffraction) frequency domain potential flow solvers
- Need a method to rapidly assess mooring system components early in the design process

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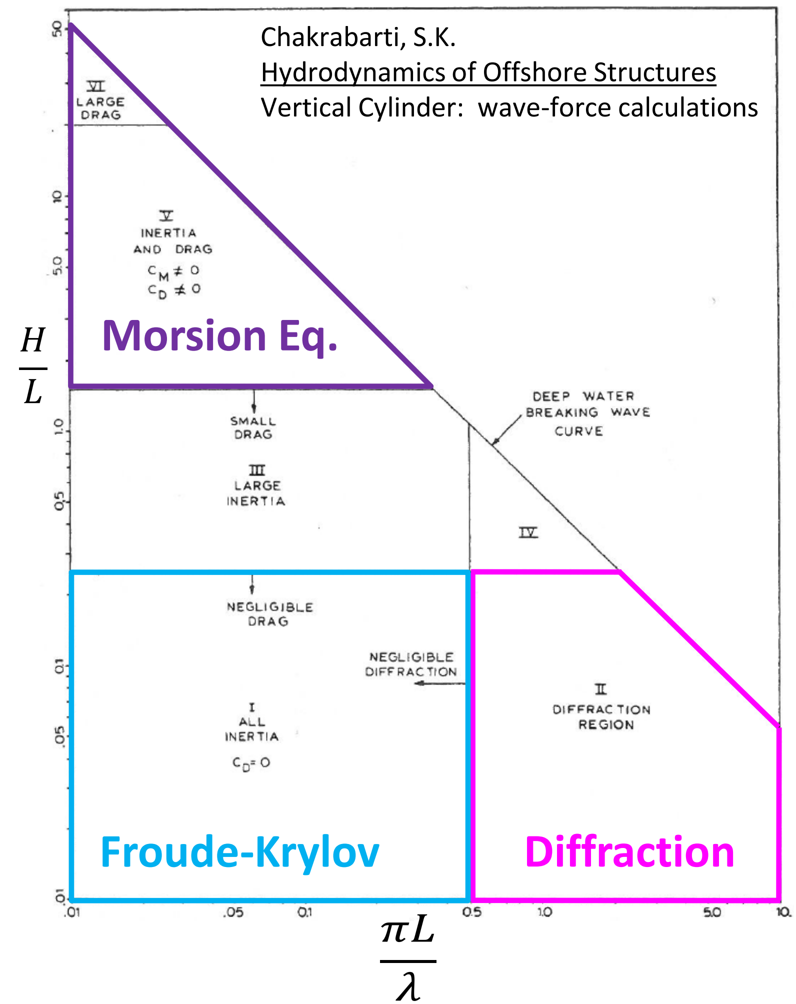
Morison Equation to Evaluate WEC Motions

- Appropriate wave-force calculation methods are specified through comparison of
  - The diffraction parameter : $\frac{\pi L}{\lambda}$
  - The wave height (H) to characteristic length ratio: $\frac{H}{L} \propto \frac{KC}{\pi}$

- Morison Equation should be used when $\frac{\pi L}{\lambda}$ is small and $\frac{H}{L}$ is large

Definitions

- L: Structures characteristic length
- λ: wavelength
- KC: Keulegan Carpenter No



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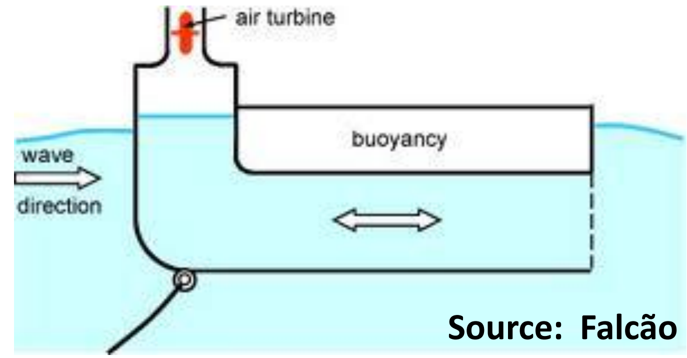
Backward Bent Duct Buoy (BBDB)

- Floating OWC device consisting of:
  - Air chamber
  - L-shaped Duct
  - Buoyancy modules
  - PTO (air turbine and generators)
- Design capitalizes on the coupled motion between the structure and the enclosed air chamber
  - Coupled motion increases frequency range over which good power conversion occurs
- PTO protection achieved through a pressure relief system.
  - Allows for wave-structure interaction to be fully described through Morison Equation



Source: Falcão

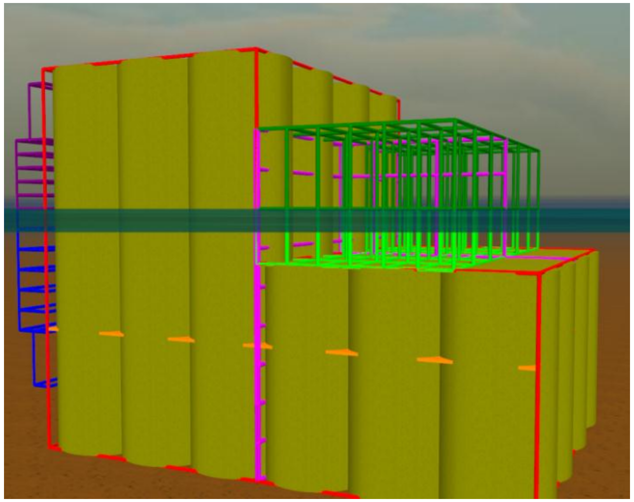

Source: CORES ¼ scale OEBuoy

Modeling Tool

- OrcaFlex used to model BBDB response
  - 3D time domain solution of equations of motion for bodies subjected to hydrodynamic loads
  - Hydrodynamic loads calculated using extended formulation of Morison's equation
- BBDB treated as a rigid body
  - Modeling methodology needs to capture hydrodynamic loads in the three translational and three rotational degrees of freedom

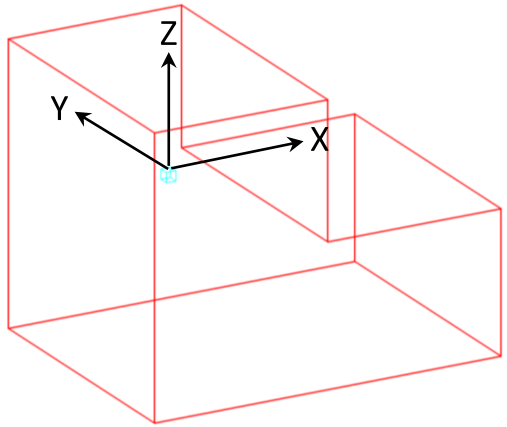
Discretization Methodology

- Model developed using an array of 6-DOF discrete bodies to capture
  - Buoyancy distribution
  - Device free flooding for the time-dependent variation of entrained water mass
  - Hydrodynamic characteristics that account for inertial and viscous effects
- Separate discrete bodies for each effect
- The array of lumped bodies is then attached to a reference body that acts as the integrand of the loading effects
- Rotational response is controlled by distribution and density of discrete bodies



Structural and Buoyancy Bodies

Structural mass and inertia prescribed at center of mass

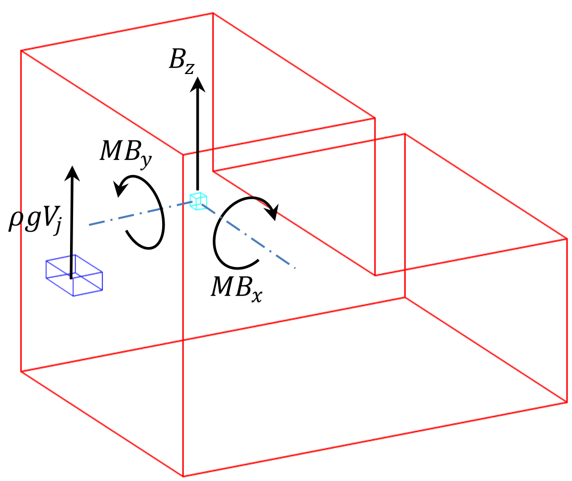


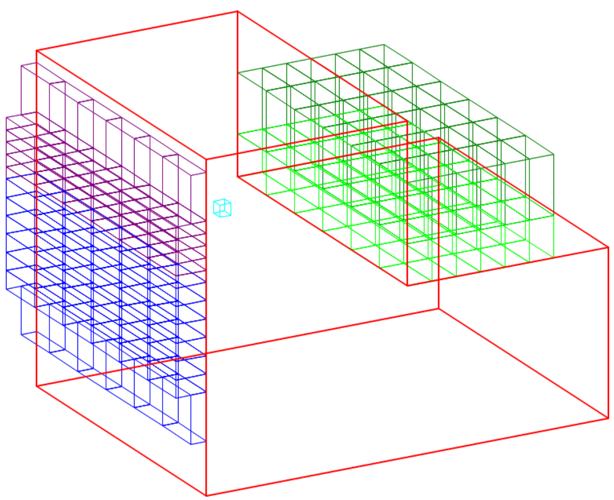
Buoyancy distribution captured by array of discrete volumes – no other properties

$$B_z = \sum_{j=1}^{N} \rho g V_j$$

$$MB_x = \sum_{j=1}^{N} [(\rho g V_j) x_j]$$

$$MB_y = \sum_{j=1}^{N} [(\rho g V_j) y_j]$$





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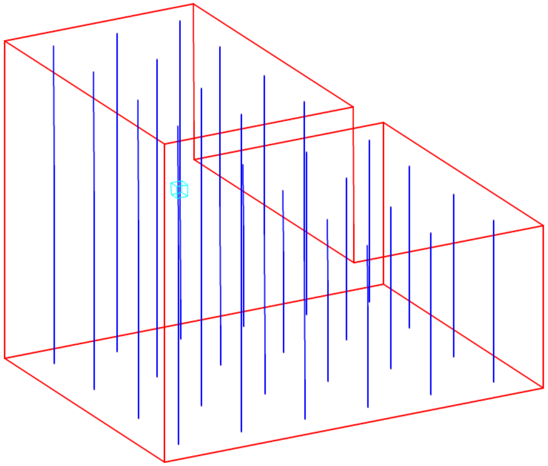
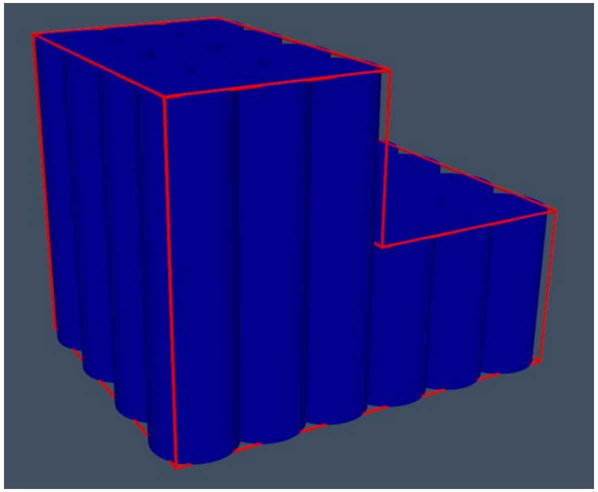
Freely Flooding Bodies

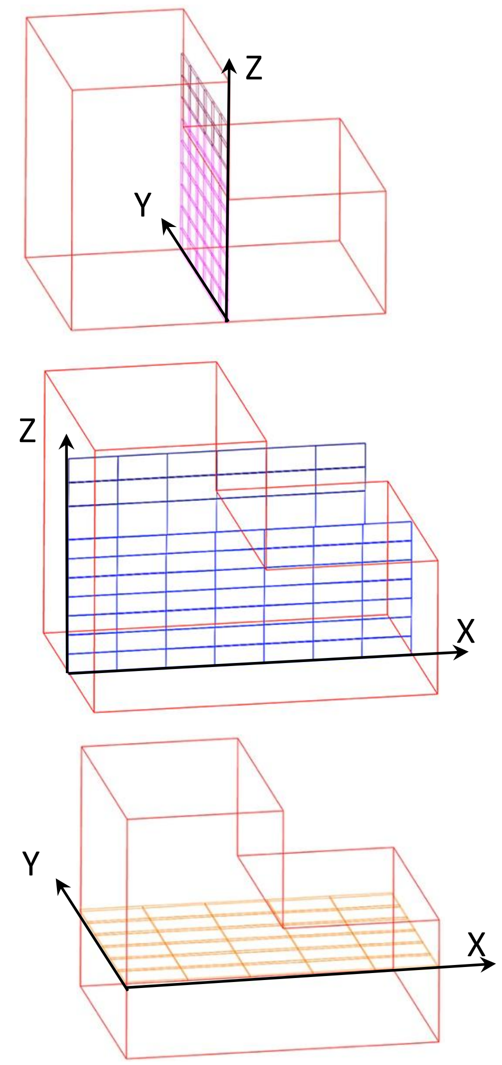
- Free flooding bodies
  - Massless with no hydrodynamic loads
  - Water volume defined by relative position to water plane
  - Captures spatial and temporal variation in free surface elevation





Hydrodynamic bodies

- Hydrodynamic bodies
  - Three sets to represent
    - X direction -> Y-Z Plane
    - Y direction -> X-Z Plane
    - Z direction -> X-Y Plane
  - Distribution of bodies readily captures rotational response
  - Discrete body properties
    - Prescribed added mass
    - Plane area and drag coefficient



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Extended Morison's Equation Formulation

For each discrete body

$$f_i = f_{inertial_i} + f_{drag_i}$$

$$= \left(\rho V \ddot{r}_{fluid_i} + \rho C_{a_i} V \ddot{r}_i\right) + \frac{1}{2}\rho C_{D_i} A_i \dot{r}_i |\dot{r}_i|$$

Inertia force due to fluid acceleration relative to earth

Inertia force due to discrete body motion in water

Drag force due to relative motion of body in water

$\rho C_{a_i} V$: Added mass term that is prescribed explicitly in this case for discrete body

A_i: Plane area for discrete body

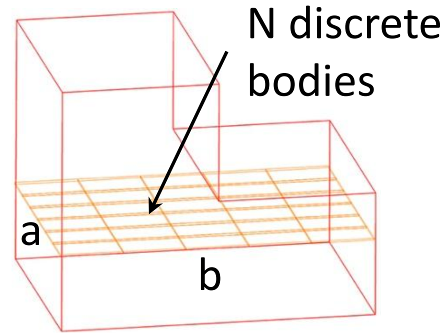
C_{D_i}: Drag coefficient for discrete body

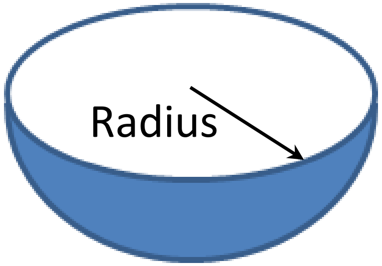
It is important to investigate impact of drag and added mass parameters on mooring components in lieu of test data to calibrate

Explicitly Defined Added Mass

- Entrained water captured by free flooding bodies
- External added mass in each direction represented by hemisphere of water
- Hemisphere radius based on characteristic radius
- Added mass apportioned equally to discrete bodies for relevant direction

<u>HEAVE</u>





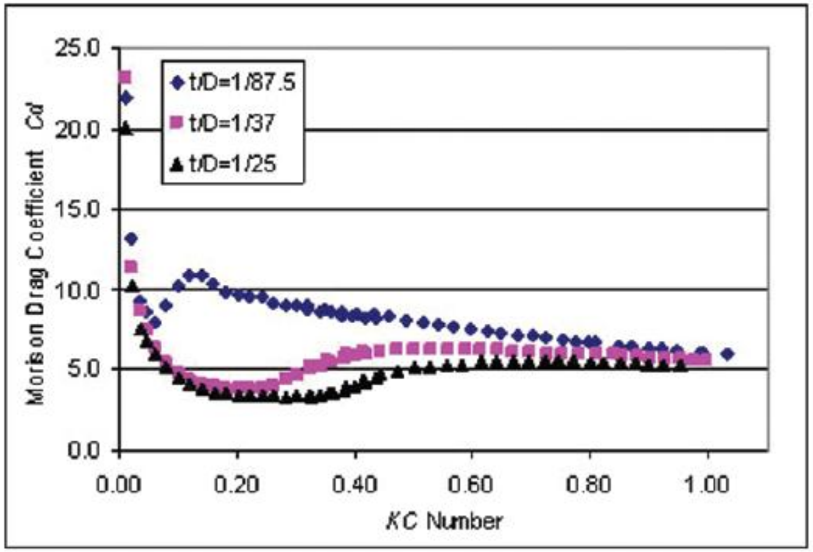
$$Radius = \sqrt{\frac{a.b}{\pi}}$$

$$Added\ Mass = \frac{\rho_w}{2}\left(\frac{4\pi}{3}(Radius)^3\right)$$

$$Added\ Mass_i = \frac{Added\ Mass}{\mathrm{N}}$$

Heave Drag Coefficient

- First estimate is to assume device is perfect wave follower
  - BBDB heave will be on the order of the wave height
- A drag factor based on steady state motion is not valid
- KC number is low so drag coefficient is higher than steady state cases (something of order of 5)



$$KC = \frac{vT}{L} = \frac{2\pi a}{L}$$

Hydrodynamics of Damping Plates at Small KC Numbers. He, H., Troesch, W., Perlin, M.. Symposium on Fluid-Structure Interaction in Ocean Engineering. 2008.

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Surge & Sway Drag Coefficients

- First estimate is to again assume device is perfect wave follower
  - Parallel to wave direction: device would oscillate according to water particle kinematics, e.g. ½ the environment wavelength
  - Perpendicular to wave direction: device is considered static
- KC number will be large parallel to the wave direction because the wavelength is large
  - Large KC numbers result in lower drag coefficients
- A small drag factor is valid for both directions due to large KC number (i.e., something of order of 1.2 to 2.0)

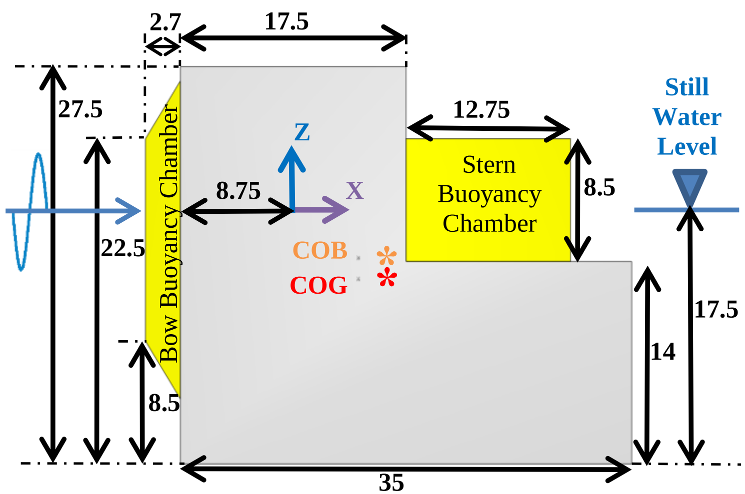
Reference Body

- All discrete bodies are attached to reference body
- Reference body has no mass, buoyancy or drag characteristics
- Resultant forces from discrete bodies are summed up at reference
  - Translational forces sum directly
  - Product of translational forces and position relative to reference body generate applied moments
- Resultant forces are summed up in every time step of calculation

Case Study to Test Modeling Methodology

Discretization Verification—Physical Design

BBDB structural properties defined from solid model.



Characteristic Length 35[m]

Structural Mass [kg]	2056940		
Front Buoyancy [m³]	802		
Aft Buoyancy [m³]	1205		
Entrained Water [m³]	14884		
COG (x,y,z) [m]	5.05	0.00	–4.74
COB (x,y,z) [m]	5.05	0.00	–3.27
Inertia at COG [kg•m²) x	3.4×10^8	0.0	0.0
Y	0.0	4.4×10^8	0.0
Z	0.0	0.0	4.5×10^8

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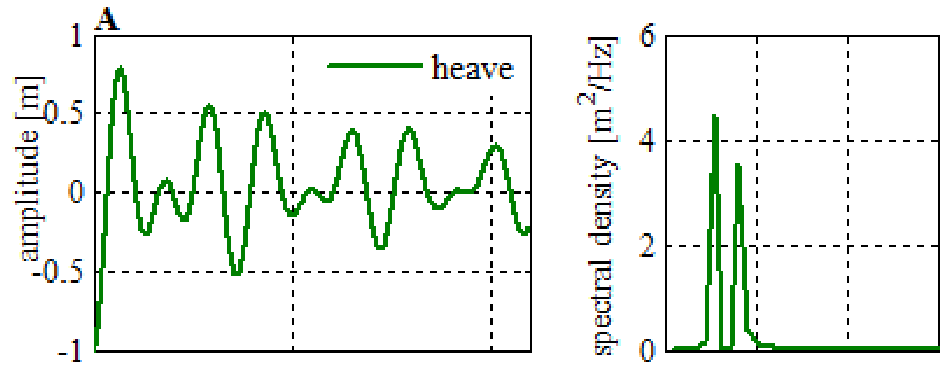
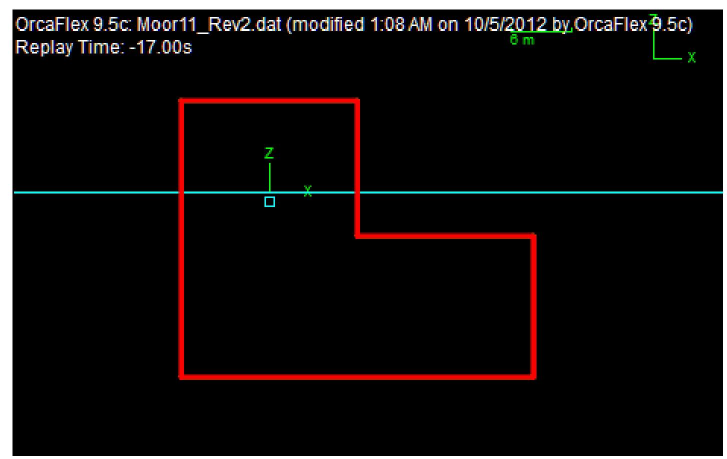
Discretization Verification—Displacement Tests

- Displace structure with unit heave in still water (in OrcaFlex)
- Record heave displacement
- Post process signal to obtain natural period
- Compare natural period to predicted value from diffraction program
- Comparison valid – small motion relative to body size
- Coupled heave pitch response captured
- Repeat for pitch and roll





OrcaFlex Heave Natural Period	18.3 sec
Potential Flow Heave Natural Period	16.1 sec

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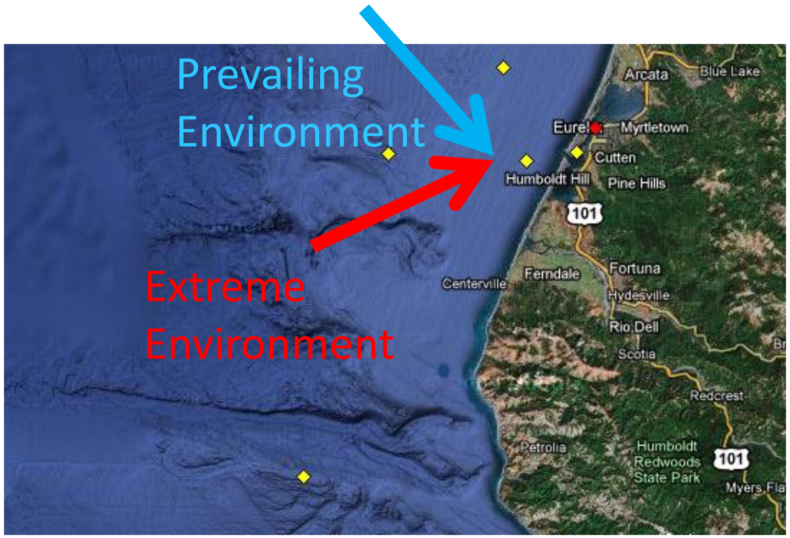
Example Extreme Environment



Northern California: Humboldt County

	Depth (h)	59.6[m]
Spectral Parameters	Significant Wave Height	11.22[m]
	Peak Period	17.26[sec]
	JONSWAP or Bretschneider	
Monochromatic Equivalent	Wave Height	21.3[m]
	Period (T)	17[sec]
	Wave Type	5th order Dean Steam
Wind	100-yr Wind at 10[m] above SWL	29.6[m/s]
	Wind Profile	constant
Current	10-yr Surface Current	0.33[m/s]
	Current Profile	Linear decrease to zero

$$\text{Wavelength } \lambda = \frac{gT^2}{2\pi} tanh\left(\frac{2\pi h}{\lambda}\right) \backsimeq 354m$$

$$\text{Diffraction Parameter} = \frac{\pi L}{\lambda} = \frac{\pi(35m)}{(354m)} = 0.3$$ **Small**

$$\text{Wave height to length ratio} = \frac{21.3m}{35m} = 0.6$$ **Large**

} Meets idealization criteria

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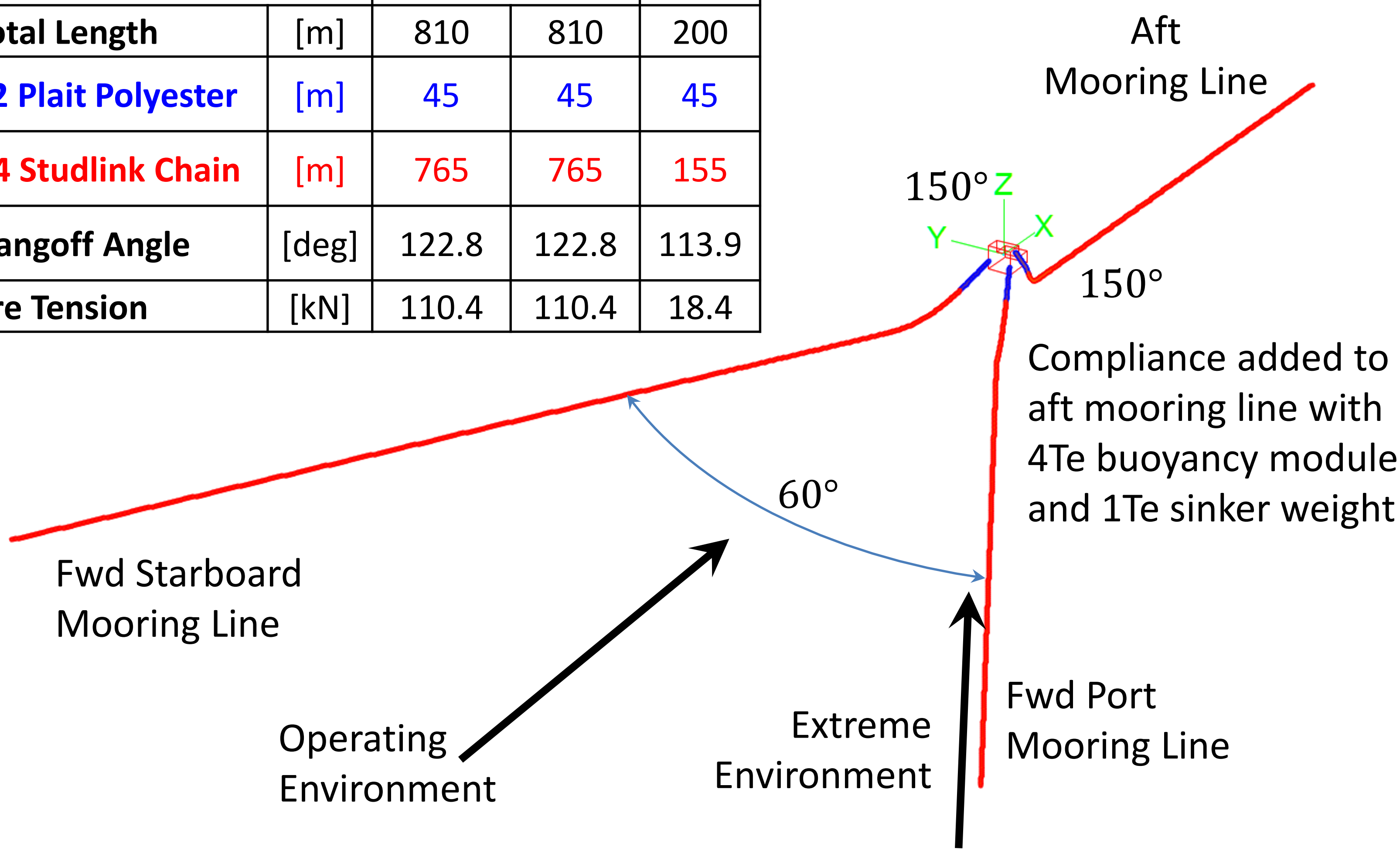
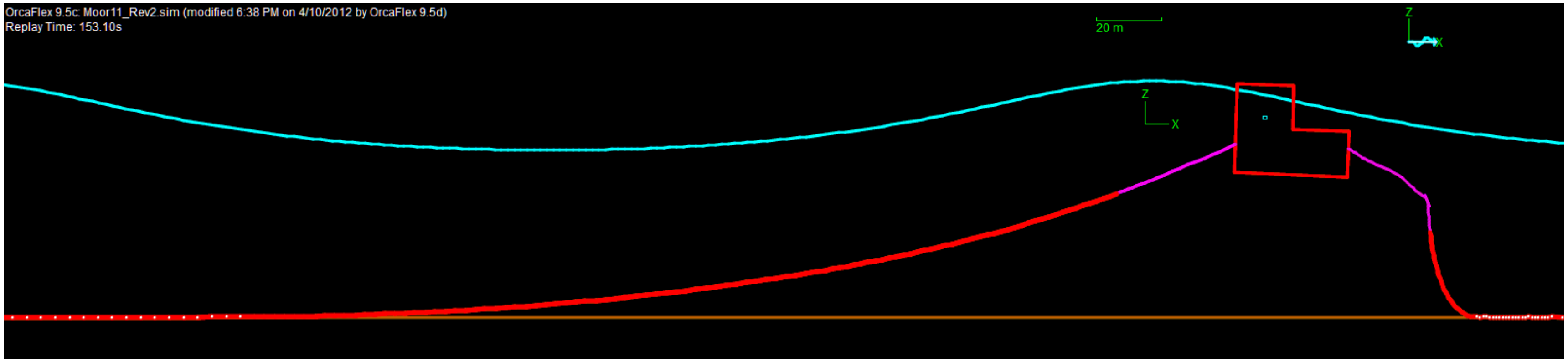
Mooring System Layout

Mooring Line		Forward		Aft
Total Length	[m]	810	810	200
12 Plait Polyester	[m]	45	45	45
R4 Studlink Chain	[m]	765	765	155
Hangoff Angle	[deg]	122.8	122.8	113.9
Pre Tension	[kN]	110.4	110.4	18.4



Mooring Performance

- Run regular wave conditions (10 cycles to obtain steady state response)
- Extract peak mooring line tensions and calculate design factor of safety
- Factors of safety – peak load 2089kN
  - Chain FOS 1.74
  - Polyester Rope FOS 2.75
- Compression in stern mooring line
- Results are for single set of drag/added mass parameters
- Test robustness by parametric study



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Parametric Study on Drag Coefficient

Test 1 is baseline

- Varied Heave Drag
- Varied Surge Drag
- Varied Sway Drag
- Combined extremes of parameters

test	C_D Specification Heave	Surge	Sway	Peak Load-Port [kN]
1	5.0	1.2	1.2	2089
2	2.5	1.2	1.2	2651
3	7.5	1.2	1.2	1940
4	5.0	2.5	1.2	3267
5	5.0	5.0	1.2	4894
6	5.0	1.2	2.5	3317
7	5.0	1.2	5.0	4383
8	5.0	2.5	2.5	4311
9	7.5	5.0	5.0	7149

Influence of drag coefficients on mooring components

test	Surge or Sway Drag Coefficient	Anchor Weight	R4 Studlink Chain Diameter
	--	Te	mm
1	1.2	5	58
4/6	2.5	8	70
5/7	5.0	11	81

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Conclusions

- Morison's equation idealization procedure is limited to applicability i.e., WEC geometry relative to environment
- If applicable:
  - Straight forward and robust
  - Can be used to quickly assess mooring system configuration and sizing of components
  - Simple analysis procedure caters for easy revision to mooring system
- Method can be used to test system response to variation in drag and added mass parameters
- Case study illustrates sensitivity of system response to assumed/theoretical drag and added mass parameters
- Method can be extend to calibration with test data as/when this becomes available

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