Introduction

In this study, the motion response of large volume structures is investigated through two examples:

- Barge model with a length of 100m.
- Ring floater model with a diameter of approximately 50m.

For large volume structures, the hydrodynamic loads are calculated based on Boundary Element Method (BEM). In traditional methods such as WADAM and AQWA, the floating body is assumed to be rigid, and the equations of motion in frequency domain are as follows:

$$\left[-\omega^2\left(M + A(\omega)\right) + i\omega\left(B_P(\omega) + B_v\right) + C + C_e\right]X(\omega,\beta) = F(\omega,\beta)$$

Where:

- M *represents the 6 by 6 body inertia matrix.*
- $A(\omega)$ *represents the 6 by 6 frequency dependent added mass matrix*
- $B_P(\omega)$ *represents the 6 by 6 frequency dependent potential damping matrix*
- B_v *represents the 6 by 6 linearized viscous damping matrix*
- C *represents the 6 by 6 hydrostatic restoring matrix*
- C_e *represents the 6 by 6 external restoring matrix*
- $F(\omega,\beta)$ *6 by 1 complex excitation force vector for frequency ω and incident wave heading angle β*

AquaSim is based on modeling the floating body with several elements where all elements have their separate DOFs such that internal forces are derived simultaneously. In AquaSim, the equations of motion are solved in time domain. The following hydrodynamic loads need to be considered in different approaches:

- Force related to added mass. Added mass is calculated in 3 motion modes, surge, sway, and heave. Added mass in 3 translational directions are distributed over the wetted surface, consistent with element distribution.
- Force related to damping. Damping is calculated in 3 motion modes, surge, sway, and heave. Damping in 3 translational directions are distributed over the wetted surface, consistent with element distribution.
- Froude-Kryloff forces are calculated based on pressure distribution from incident potential.
- Diffraction forces are calculated based on pressure distribution by solving the diffraction problem in frequency domain such that the total pressure includes diffraction.
- AquaSim keeps track of the incident wave elevation and introduces pressure to all elements below the instantaneous water surface.

Comparing the difference between typical frequency domain methods with the time domain method in AquaSim, the main difference is from the forces arising from added mass and damping:

- In frequency domain methods, added mass and damping can be considered in rotational modes such as roll, pitch, and yaw modes.
- In AquaSim, the added mass and damping is accounted for in a different approach. Take the pitch mode for example, different segments of the panel model can have different longitudinal and vertical displacement from the pitch mode. The added mass and damping in x and z directions are calculated according to its corresponding surge and heave modes. In other words, the added mass and damping in pitch mode is considered by the added mass and damping under surge and heave modes.
- From an engineering point of view, the added mass under pitch mode can be approximated by the surge and heave modes. This depends on the panel model configuration. For the barge model, the interaction between different segments under pitch mode is less influenced, compared with that of the ring pontoon model.

The hydrodynamic responses of the barge model and ring pontoon models are described in detail in the following sections.

Motion Response of Barge Model

Barge Model Description

The barge is shape like a box and the main dimensions are as follows:

- Length: 100 m
- Width: 20 m
- Depth: 12 m
- Draft: 6 m
- Displacement volume: 12,000 m^3

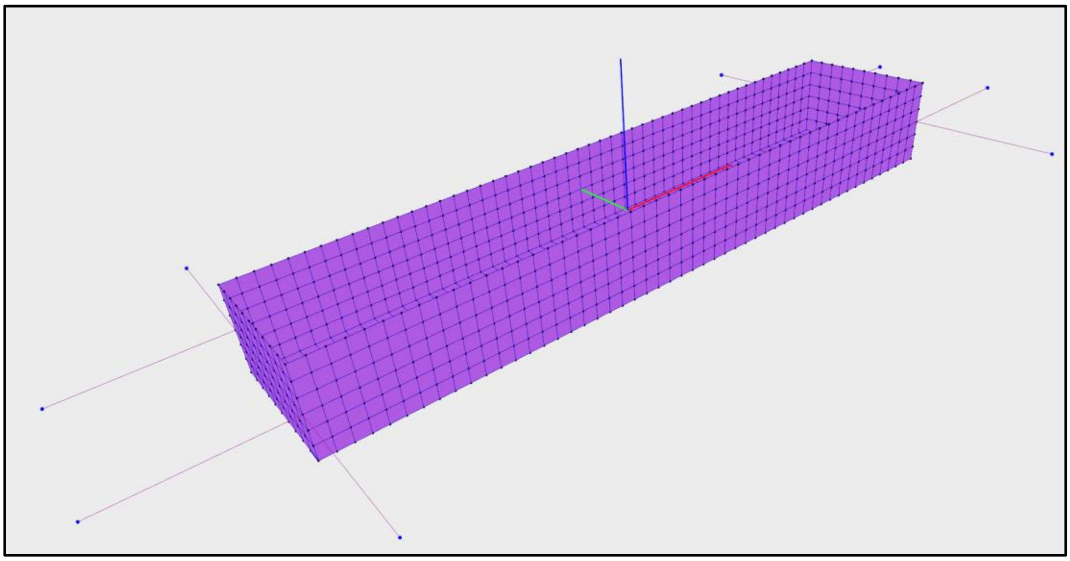


Figure 1: General view of barge model (length of 100m, width of 20m, draft of 6m).

There are three components included in the barge model. Hydrodynamic loads act on membrane elements component (ShipSurface), while component (Frames) contribute with stiffness in the model. Component (ShipSurface) takes the buoyance force and component (Frames) withstand gravity loads.

- Component (Frames): Beam element, which provides main stiffness of barge model.
- Component (ShipSurface): Membrane elements used to calculate hydrodynamic force based on boundary element method. Hydrostatic forces are also calculated from membrane elements.
- Component (MooringLines): Truss element. Soft springs to provide surge, sway, and yaw restoring forces for the barge model.

In the following subsections, different components are described in detail.

Component (Frames)

A general view of component (Frames) is shown in Figure 2. The purpose of the frame model is to provide sufficient stiffness for the barge model. Membrane elements based on shell elements has numeric convergence problems for global stiffness. Hence, component (Frames) is mainly used to provide stiffness, which also can reduce the computational cost significantly.

Stiffness properties are shown in Figure 3. The main purpose is to ensure that the barge is rigid. The reason is twofold. Firstly, flexibility of the structure may increase the convergence time. Secondly, the rigid body motion is to be compared with the results from WADAM.

Hydrodynamic properties are shown in Figure 4. The frame structures are assumed to have:

- Zero volume, no hydrostatic force or excitation forces.
- Zero added mass and damping.
- Zero drag, lift and frictional coefficients.
- Total mass is equal to the mass displacement.

Component (Frames) are supposed to take no hydrodynamic loads. The gravity loads in the water is almost identical to the gravity loads in air, which is identical to the mass displacement in mean position.

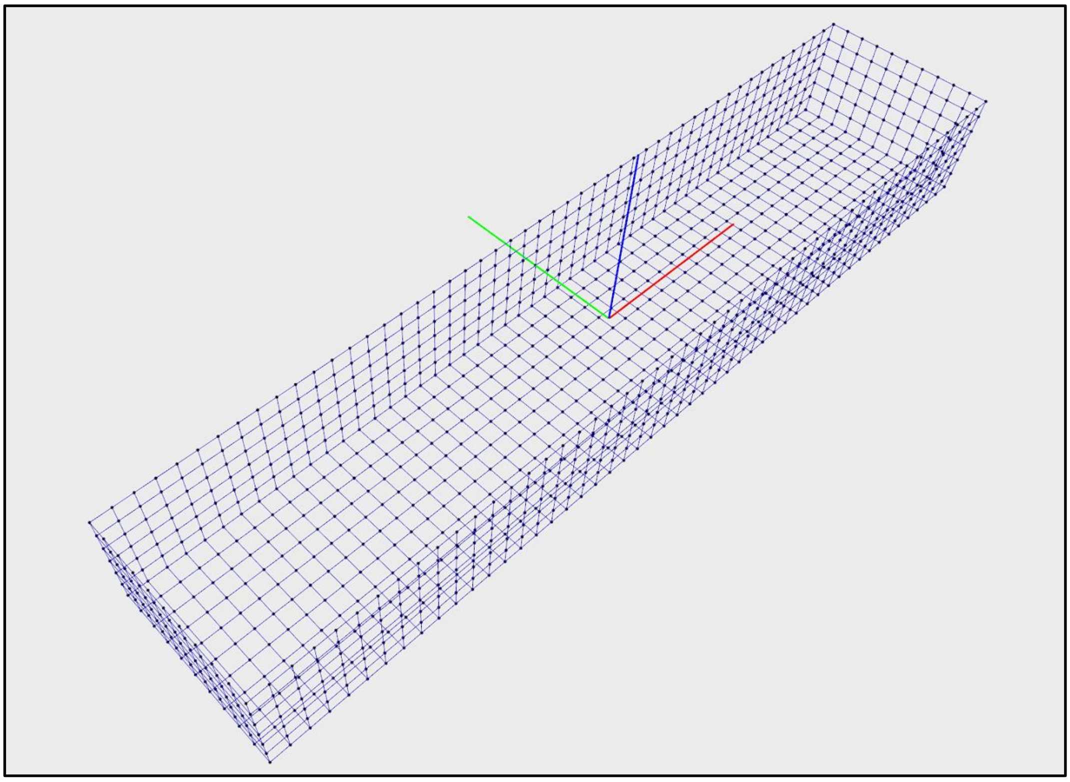


Figure 2: Component (Frames).

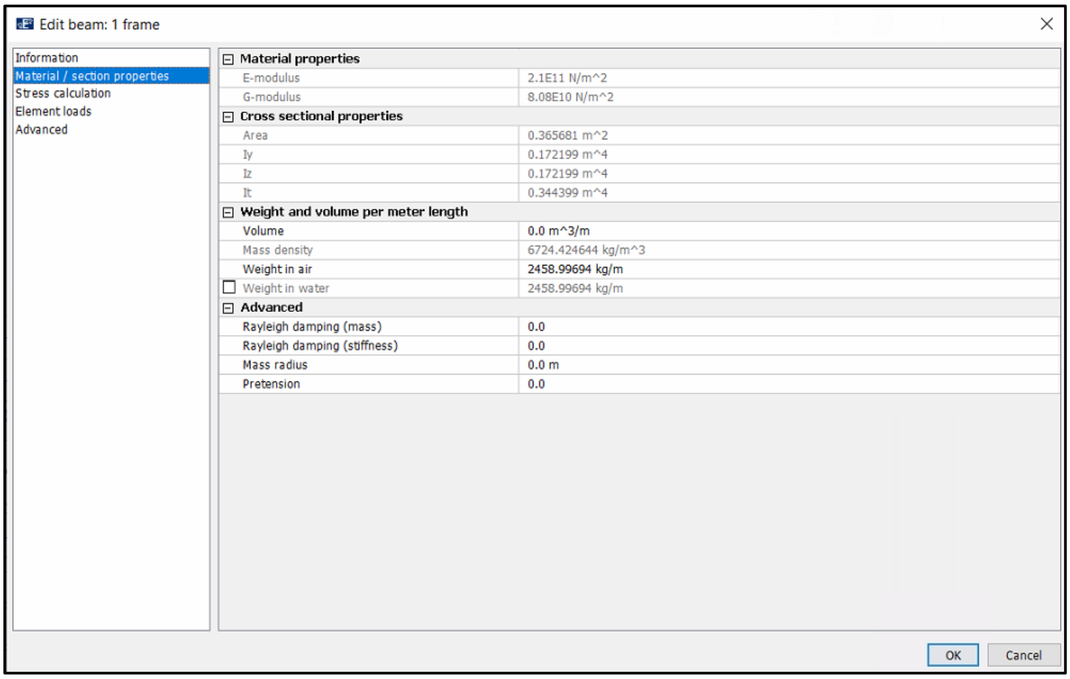


Figure 3: Cross sectional stiffness properties for beam elements in component (Frames).

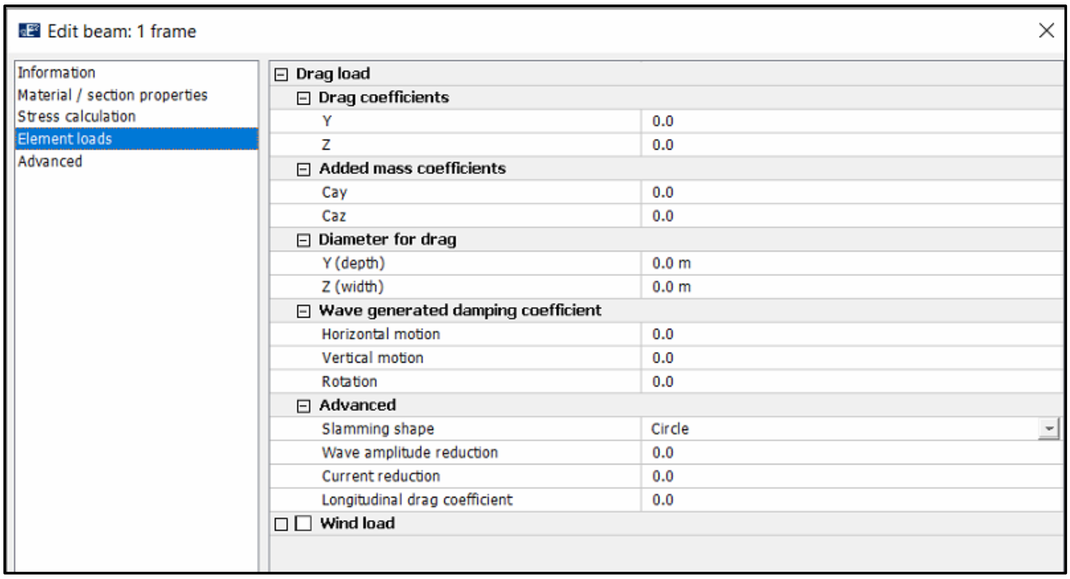


Figure 4: Cross sectional stiffness properties for beam elements in component (Frames).

Component (ShipSurface)

For component (ShipSurface), membrane elements are built as shown in Figure 5. The membrane elements are supposed to take the following loads:

- Hydrostatic loads such as buoyancy loads and restoring forces.
- Excitation forces due to Froude-Kryloff forces and diffraction forces.
- Radiation forces are accounted for by added mass and damping distributed over wet surface.

Using traditional Hydrodynamic Software (such as WADAM or AQWA), added mass and damping are accounted for by coefficient matrices (size 6x6) for six degrees of rigid body motions, i.e. surge, sway, heave, roll, pitch, and yaw.

In AquaSim, added mass and damping are considered in three translational directions (surge, sway and heave) since added mass and damping are to be distributed over the wetted surface. From theoretical point of view, the magnitude A11, A22, A33, B11, B22, and B33 are identical to those based on boundary element method.

The following crossing terms such as A13 and B13 are not accounted for in the current analysis. From engineering point of view, A11, A22, and A33 are dominant while terms A13 and B13 have quite limited influence over the global motions. Hence, it is reasonable to ignore the effects due to these cross-terms. In other words, cross-terms need to be evaluated before the AquaSim simulation is carried out to make sure that those terms have limited influence over the global response.

In BEM software such as WADAM or AQWA, added mass terms A44, A55, and A66 are to be calculated by rigid motion roll, pitch, and yaw directly. In AquaSim, added mass A55 are accounted for by distributing added mass A11 and A33 over the wetted surface induced by rigid body motion surge and sway, and that is an indirect approach. Terms A44, A55 and A66 are calculated following the same approach. In other words, the added mass effects similar to A44, A55, and A66 in AquaSim may be slightly different than those used in BEM software.

Material properties and hydrodynamic properties for membrane elements are illustrated in Figure 6 and Figure 7. Membrane elements provide dummy stiffness, and high stiffness needs to be avoided. No drag, lift or skin friction forces are assumed for the barge motion.

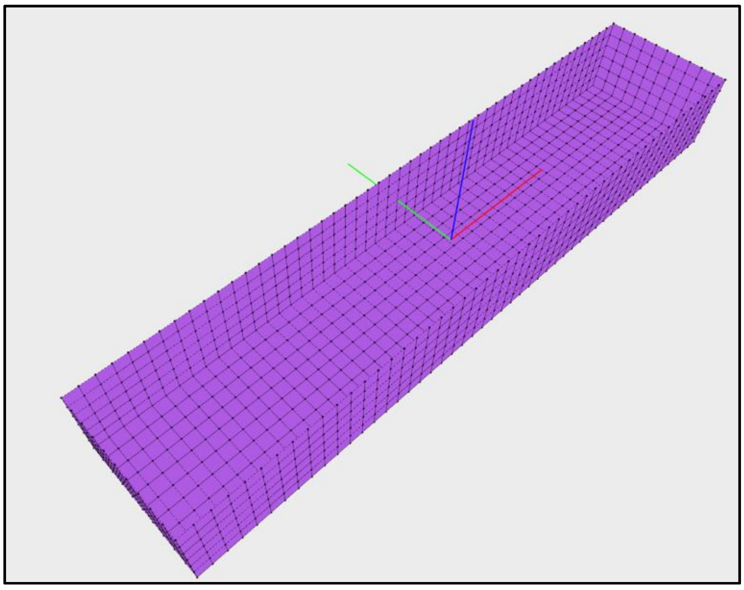


Figure 5: Membrane element, mesh size of 2m. There is a total of 1,220 membrane elements, and 860 membrane elements are under the still water level.

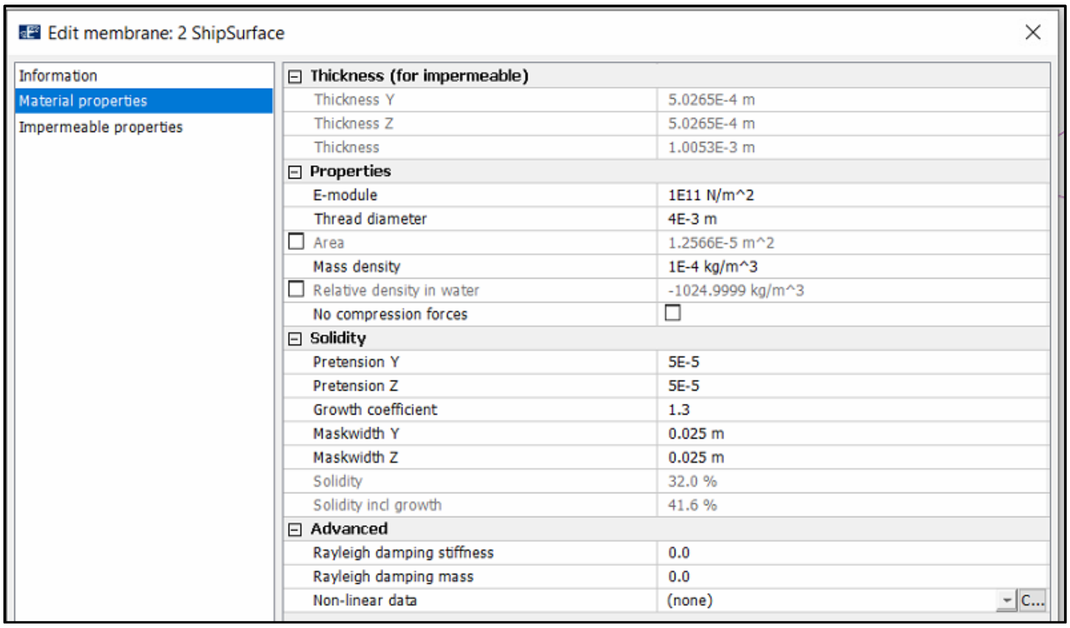


Figure 6: Material properties for membrane elements component (ShipSurface).

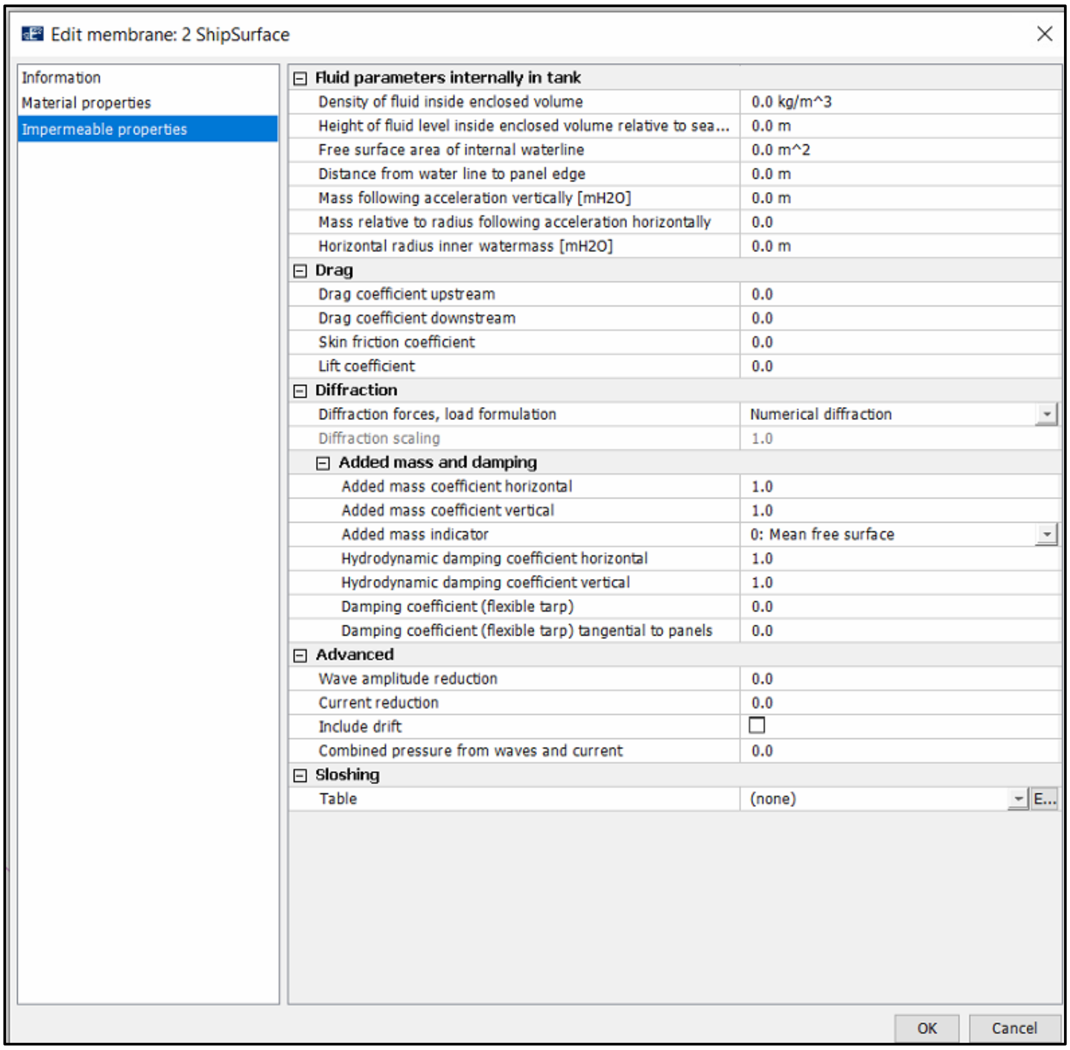


Figure 7: Hydrodynamic properties for membrane elements component (ShipSurface).

Component (MooringLines)

Truss element is used for component (MooringLines). The purpose of component (MooringLines) is to restrict large rigid body motions, especially yaw motion. The excitation forces due to diffraction effects are dependent on the heading. Diffraction forces are calculated in frequency domain for mean position, while considering a specific heading. Large yaw motion may result in non-linear motion response.

Stiffness properties are shown in Figure 9, and Rope_14mm is supposed to provide limited stiffness in the horizontal plane. The natural periods introduced by the mooring lines are above 100s.

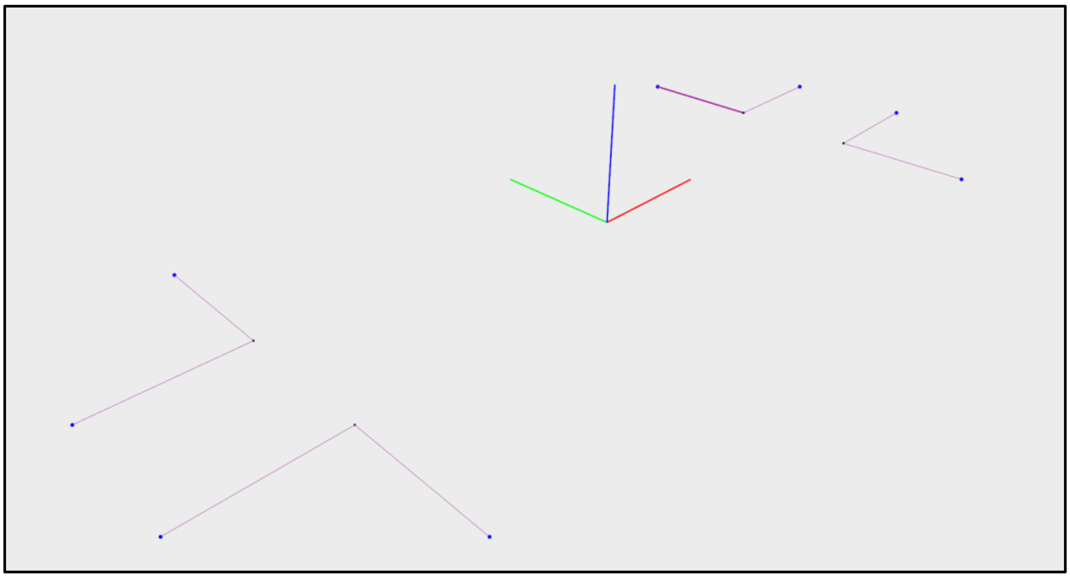
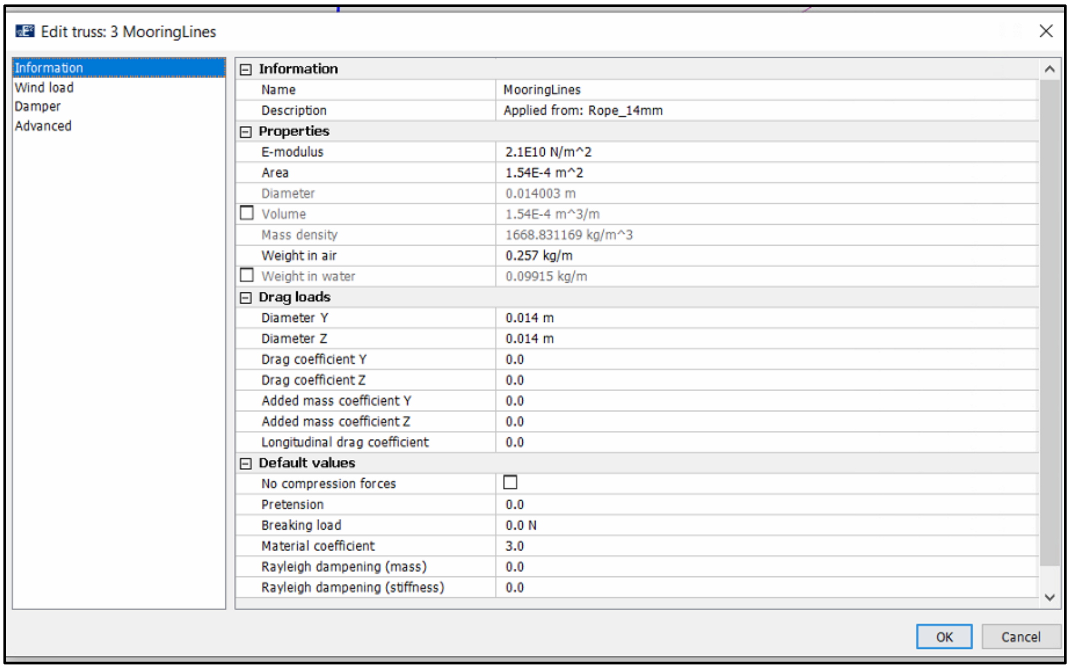


Figure 8: Mooring lines connected to the barge.



Edit truss: 3 MooringLines

Information
Wind load
Damper
Advanced

Information	
Name	MooringLines
Description	Applied from: Rope_14mm
Properties	
E-modulus	2.1E10 N/m^2
Area	1.54E-4 m^2
Diameter	0.014003 m
Volume	1.54E-4 m^3/m
Mass density	1668.831169 kg/m^3
Weight in air	0.257 kg/m
Weight in water	0.09915 kg/m
Drag loads	
Diameter Y	0.014 m
Diameter Z	0.014 m
Drag coefficient Y	0.0
Drag coefficient Z	0.0
Added mass coefficient Y	0.0
Added mass coefficient Z	0.0
Longitudinal drag coefficient	0.0
Default values	
No compression forces	☐
Pretension	0.0
Breaking load	0.0 N
Material coefficient	3.0
Rayleigh dampening (mass)	0.0
Rayleigh dampening (stiffness)	0.0

OK Cancel

Figure 9: Mooring line properties.

Time Domain Simulations

As shown in Figure 10, time domain simulations are carried out for 17 regular waves. The wave amplitude is 1m. Wave period ranges from 2s to 20s. Wave Heading is 180 deg. Time domain parameters are shown in Figure 11. For each wave cycle, 50 steps are used and in total there are 800 steps. In total, each run has 16 cycles. Figure 12 show the typical snapshoot of barge response under regular waves. For regular waves with period of 12s, time history of motion response including surge, heave, and pitch motions is shown in Figure 13. The Response Amplitude Operator can be calculated as the average difference value of peaks and troughs.

☑	Nr	Amp[m]	T[s]	V[deg]	cX[m/s]	cY[m/s]	wX[m/s]	wY[m/s]	Comment	Group
☑	1	1	2	180.0	0	0	0	0		0
☑	2	1	3	180.0	0	0	0	0		0
☑	3	1	4	180.0	0	0	0	0		0
☑	4	1	5	180.0	0	0	0	0		0
☑	5	1	6	180.0	0	0	0	0		0
☑	6	1	7	180.0	0	0	0	0		0
☑	7	1	8	180.0	0	0	0	0		0
☑	8	1	9	180.0	0	0	0	0		0
☑	9	1	10	180.0	0	0	0	0		0
☑	10	1	11	180.0	0	0	0	0		0
☑	11	1	12	180.0	0	0	0	0		0
☑	12	1	13	180.0	0	0	0	0		0
☑	13	1	14	180.0	0	0	0	0		0
☑	14	1	15	180.0	0	0	0	0		0
☑	15	0	16	180.0	0	0	0	0		0
☑	16	0	18	180.0	0	0	0	0		0
☑	17	0	20	180.0	0	0	0	0		0

Figure 10: Regular wave list.

⊟ Time serie	
Preincrement	2
Max iterations pr step	150
Num total steps for waves	800
Num steps for one wave	50
Convergence criteria	1.0
Change dynamic convergence criteria	0.0
Current reduction method	Energy method
Current reduction type	Deformed by current and waves
Infinite depth	☑
Depth (wave profile)	-1.0 m
☐ Cresting wave factor	0.0
⊟ Bottom	
Bottom contact	☐
Bottom depth	-100.0 m
Use terrain as bottom	☐
Bottom parameter	1.0
Bottom friction	0.0
Dynamic vertical friction	0.0
Dynamic horizontal friction	0.0
⊟ Advanced	
Water volume correction	None
Reported steps	1
Convergence accelerator	0.0
Newmark damping	0.5
Analysis type	Normal
Type of mass	Lumped mass
Buckling/eigen period analysis	☐ E...
Non linear density field	☐ E...
Membrane normals are verified	☑
Enable python integration	☐

Figure 11: Time domain properties.

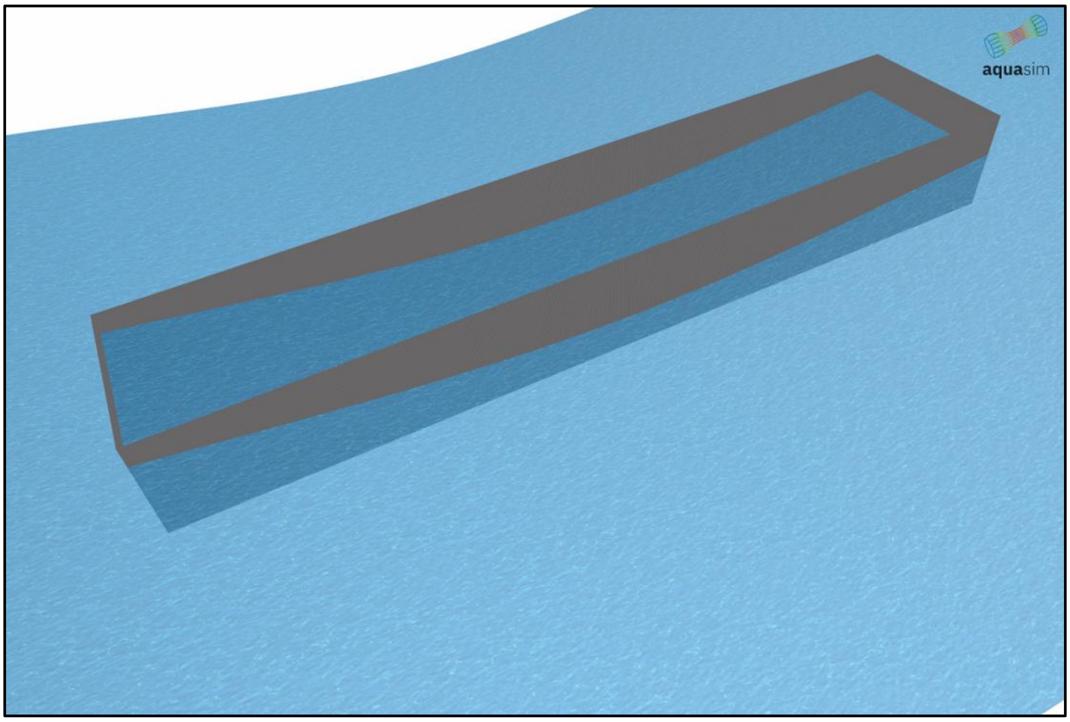


Figure 12: General view of barge motion response under regular waves. Incident wave profile is illustrated. Diffracted waves are not shown visually in the time domain simulations, but resulting pressure from waves can be chosen and shown distributed over the wetted surface. Wave profile is for illustration purposes presented with a wave amplitude of 3m.

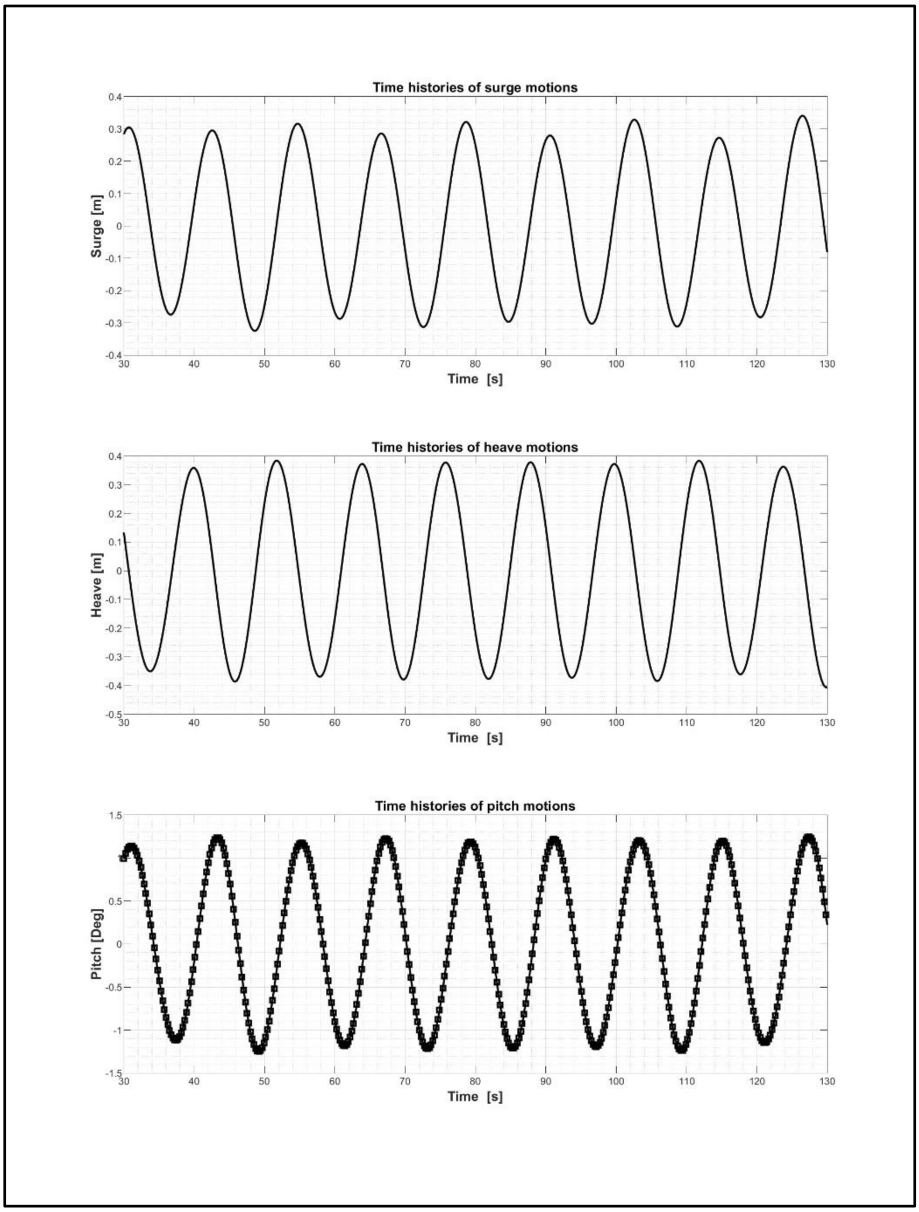


Figure 13: Time history of surge, heave, and pitch motion under regular waves (Period = 12 s).

Comparisons of Hydro Properties

Figure 14 to Figure 19 show the added mass and damping calculated from AquaSim compared with WADAM (in the plot, it is noted as "HydroD"). Consistent added mass and damping results are shown from both software. Figure 20 show the horizontal added mass distribution Figure 21 show the vertical added mass distribution.

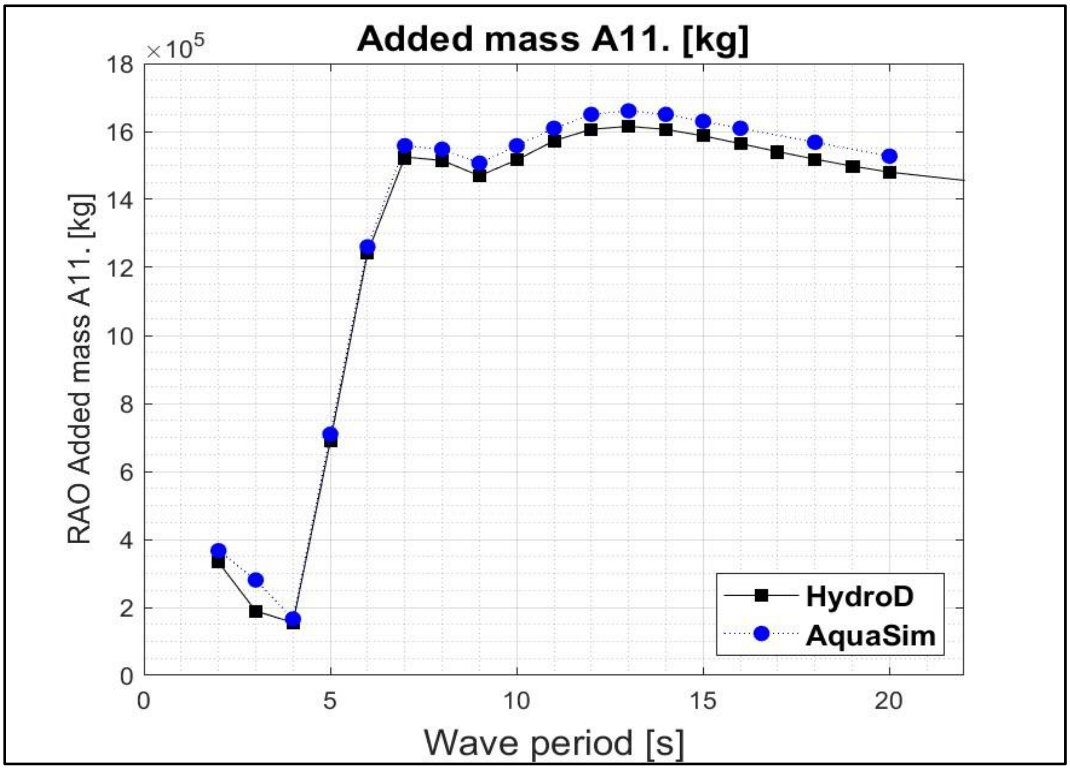


Figure 14: Added mass comparison – A11.

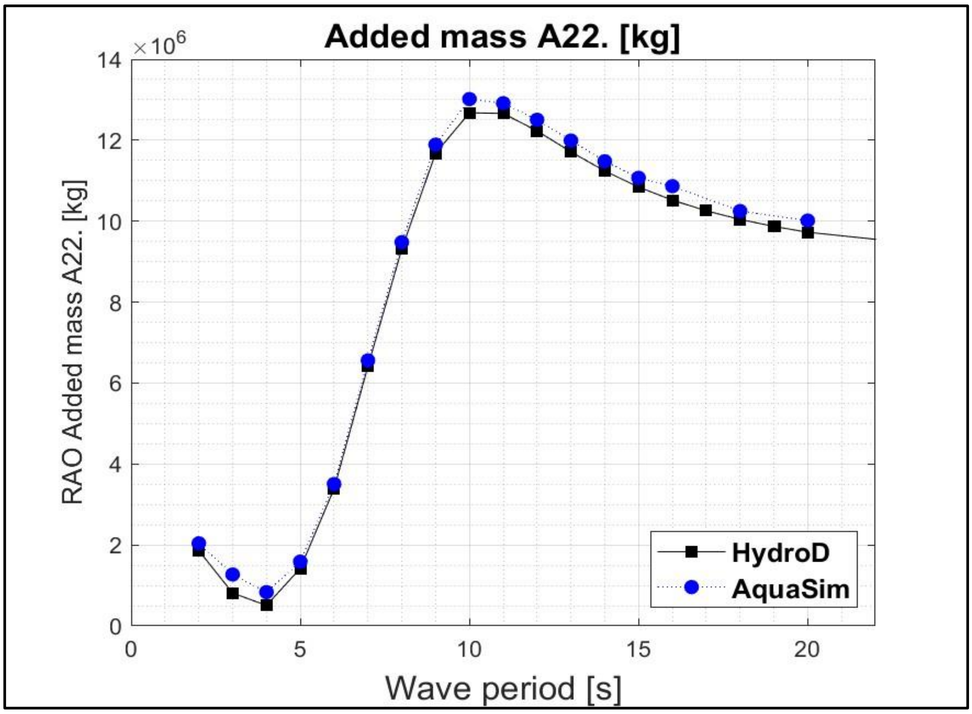


Figure 15: Added mass comparison – A22.

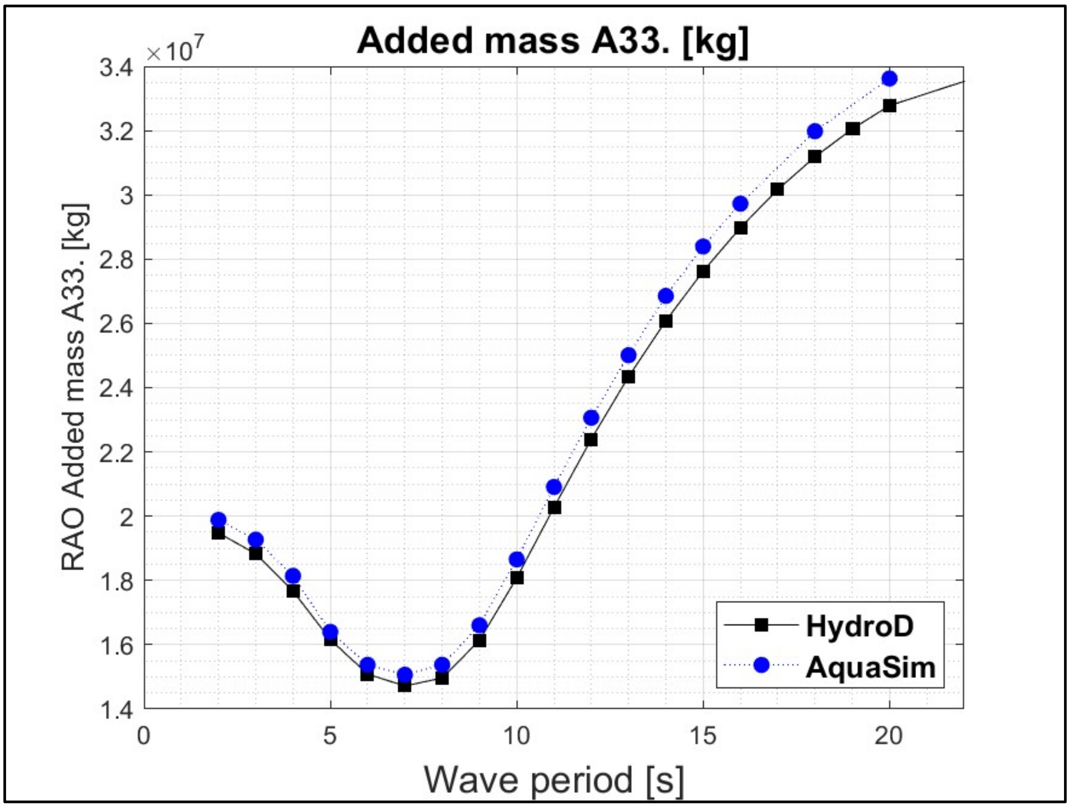


Figure 16: Added mass comparison – A33.

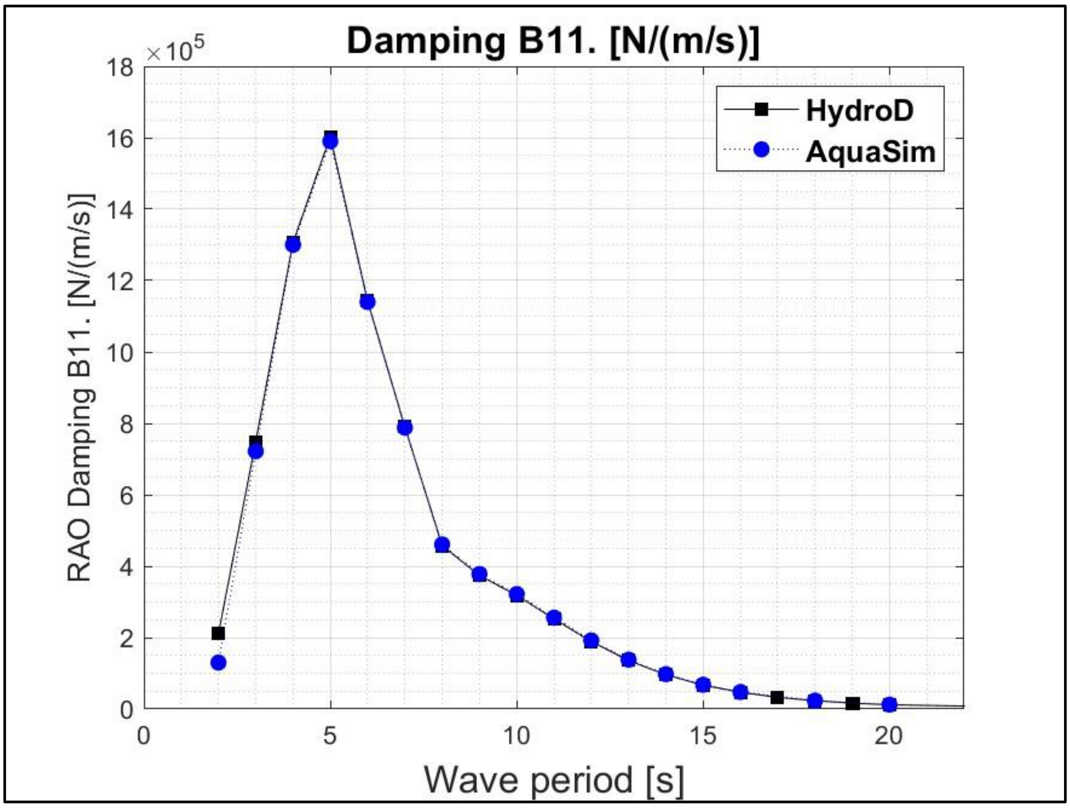


Figure 17: Damping comparison – B11.

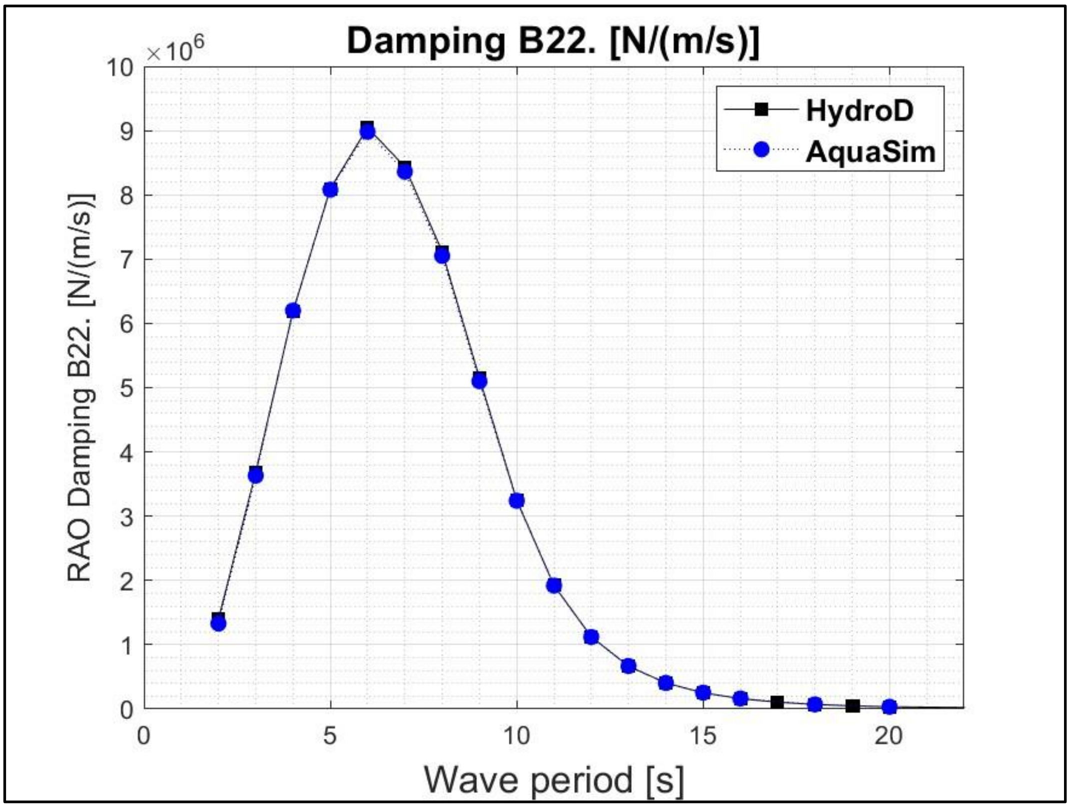


Figure 18: Damping comparison – B22.

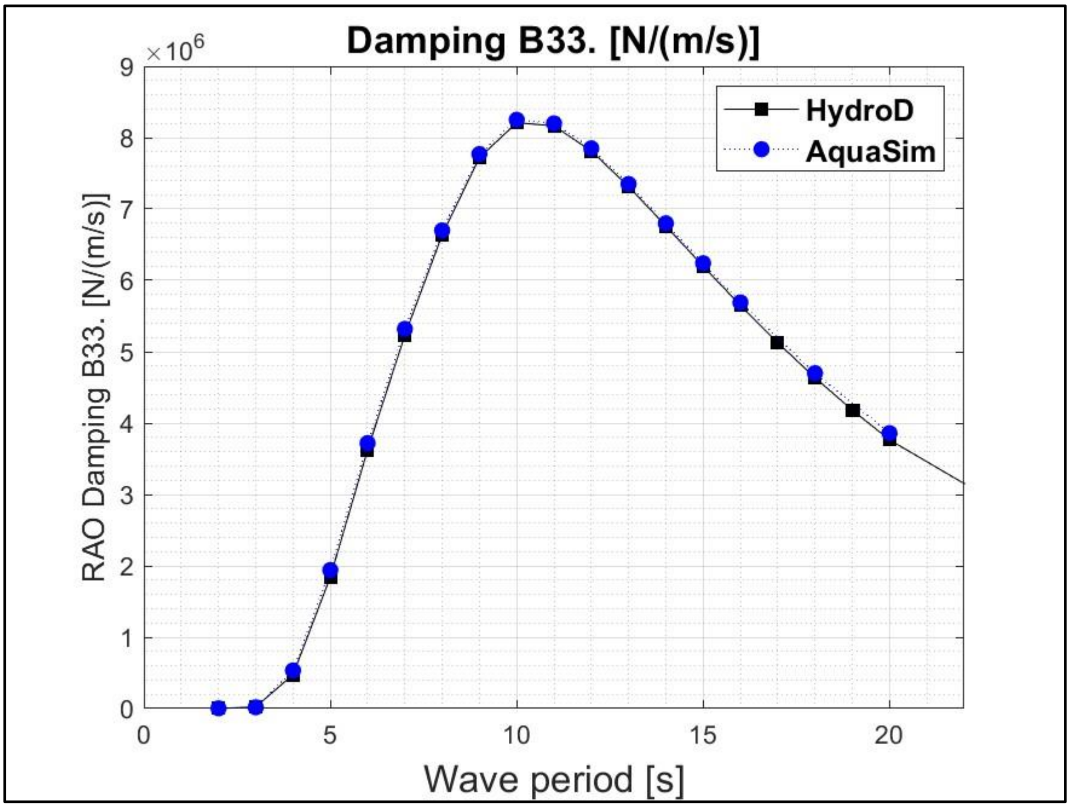


Figure 19: Damping comparison – B33.

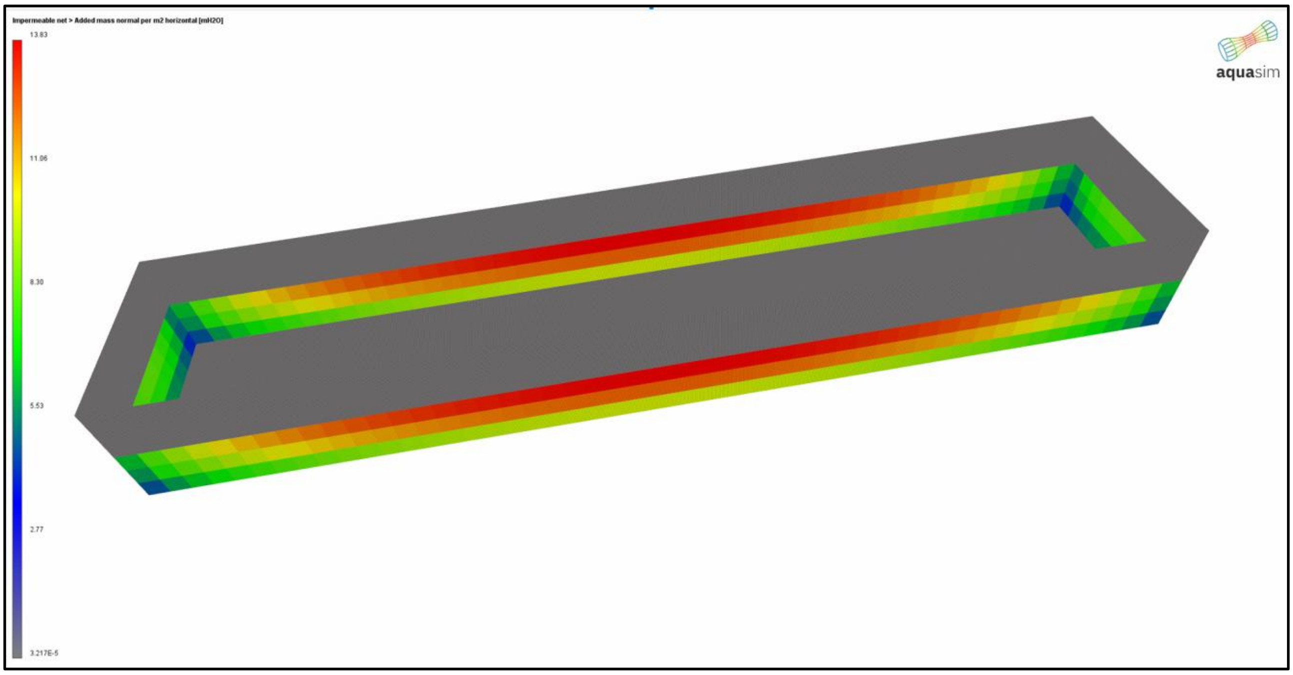


Figure 20: Horizontal added mass attached to membrane elements.

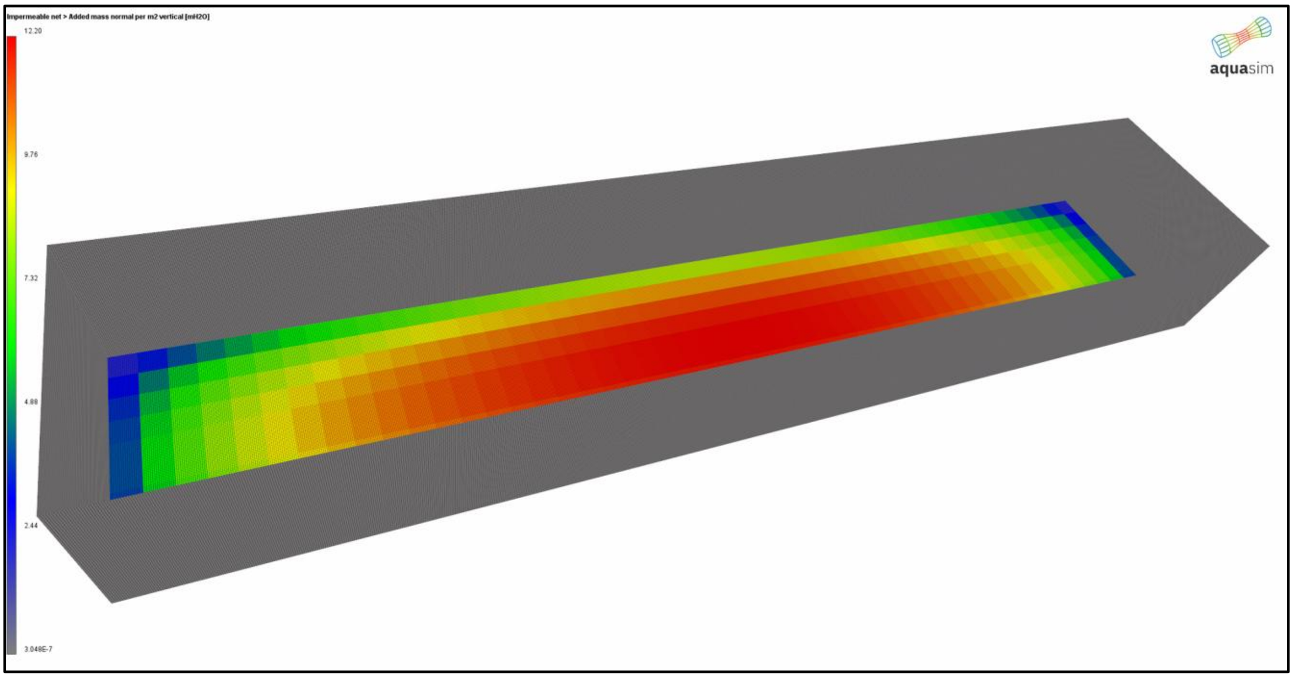


Figure 21: Vertical added mass attached to membrane elements.

Comparisons of Motion Responses under Head Seas

In Figure 22 to Figure 24, surge, heave, and pitch motions under head seas are compared between the results from AquaSim and WADAM. Motion response from AquaSim is identical to that from WADAM. This verified that the time domain results from AquaSim for the barge floater are reliable.

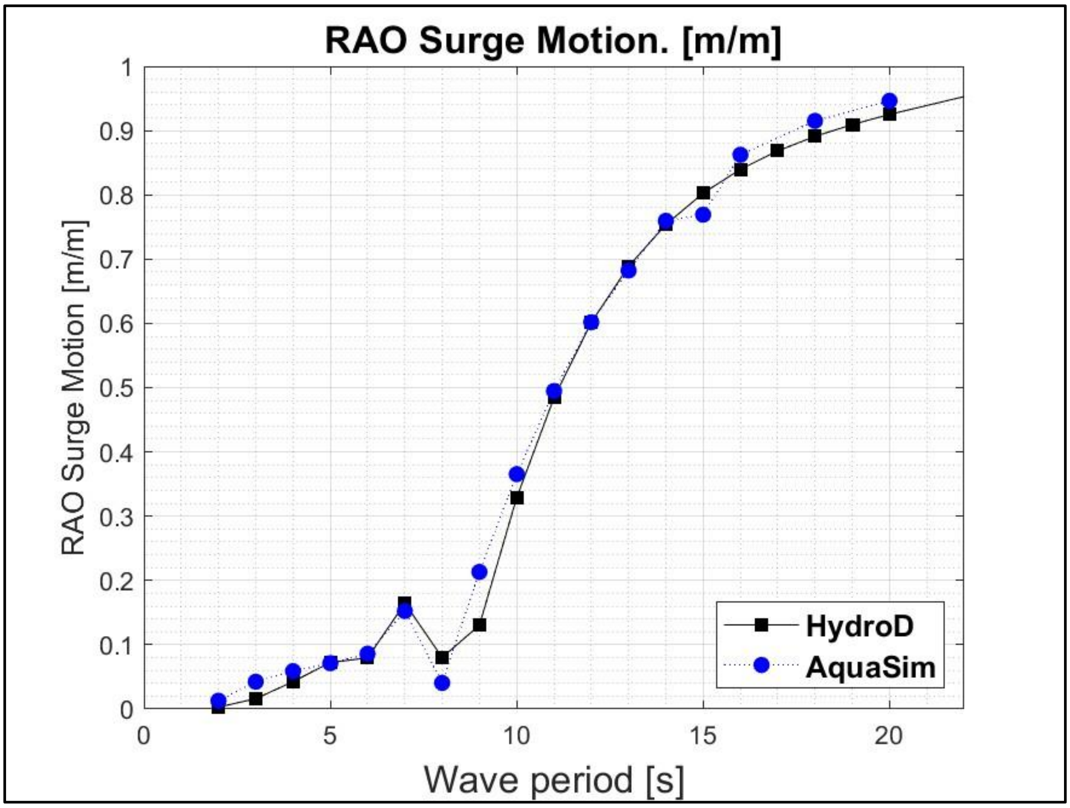


Figure 22: Surge motion comparison under head seas.

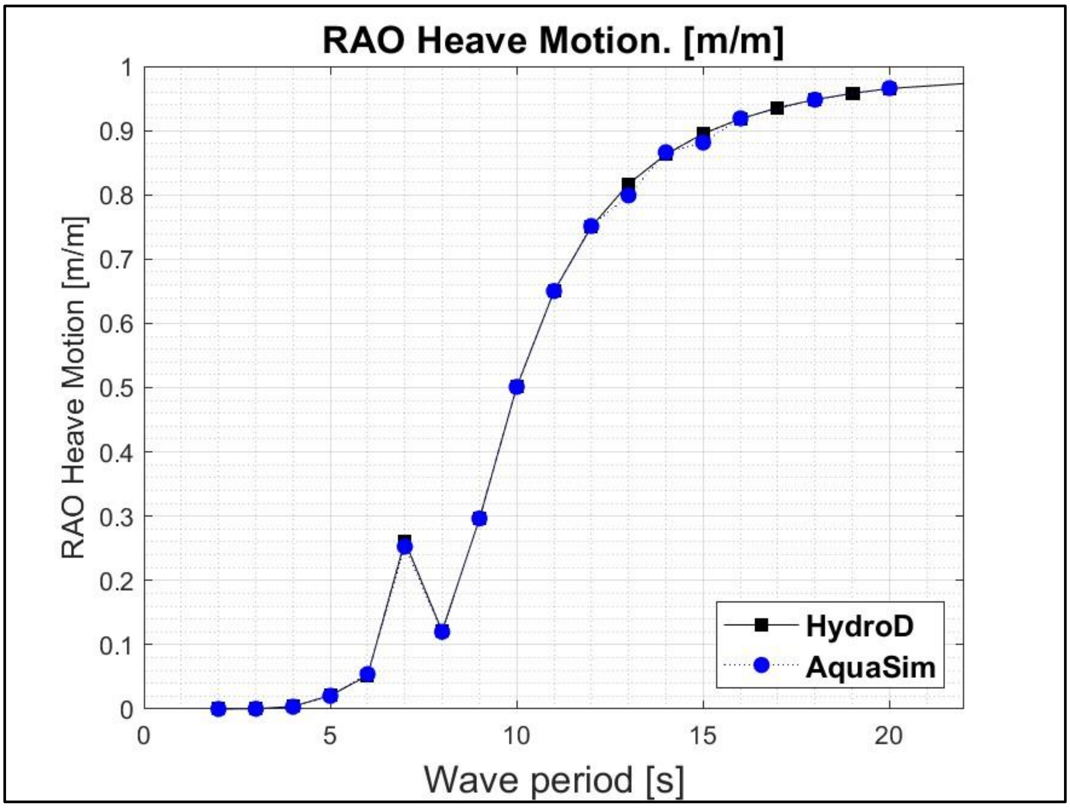


Figure 23: Heave motion comparison under head seas.

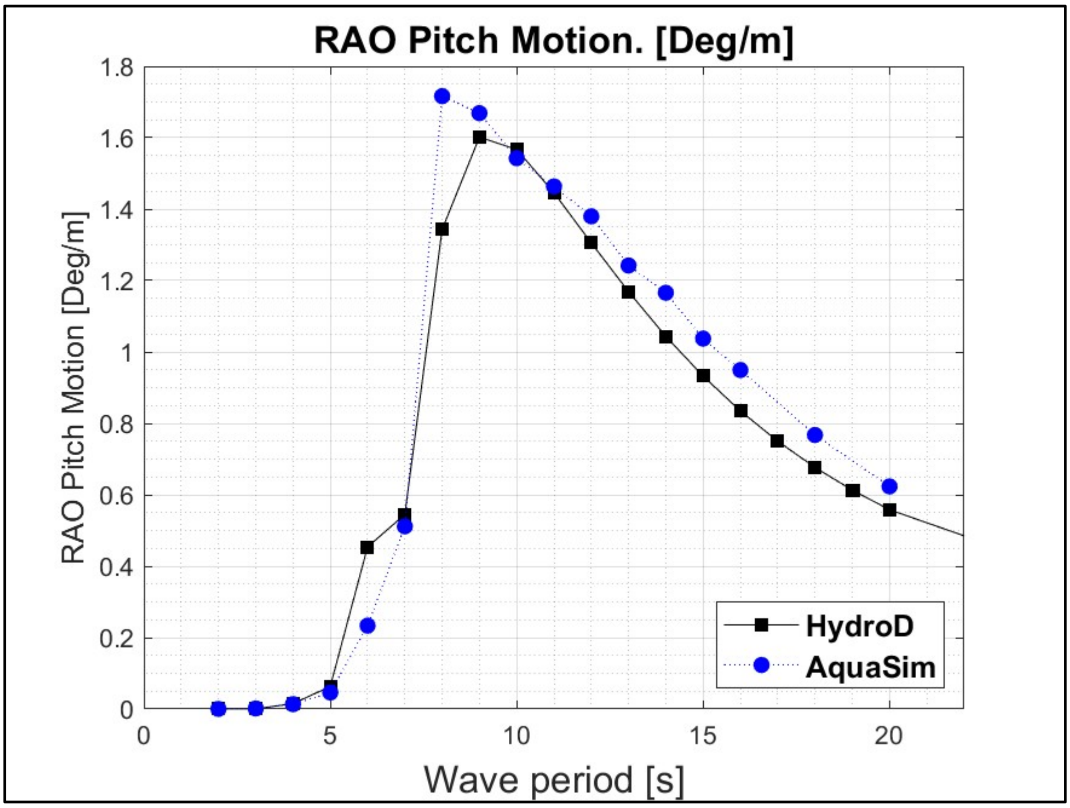


Figure 24: Pitch motion comparison under head seas.

Comparisons of Added Mass A55

In AquaSim, there is in fact no term called added mass A55. For comparison purposes, it is of interest to compare the added mass A55 from WADAM with the equivalent added mass A55 from AquaSim.

The equivalent added mass A55 is calculated through an approximate method. In fact, the added mass A33 is not strictly evenly distributed. It can be assumed that the added mass A33 is evenly distributed along the longitudinal direction. The so-called A55 term in AquaSim can be calculated by integration along the longitudinal direction.

Added mass A55 is compared in Figure 25. Although certain discrepancies exist for A55, the general trend in A55 is quite similar. This implies that the engineering approach is acceptable considering that the motion response from both methods show quite consistent results.

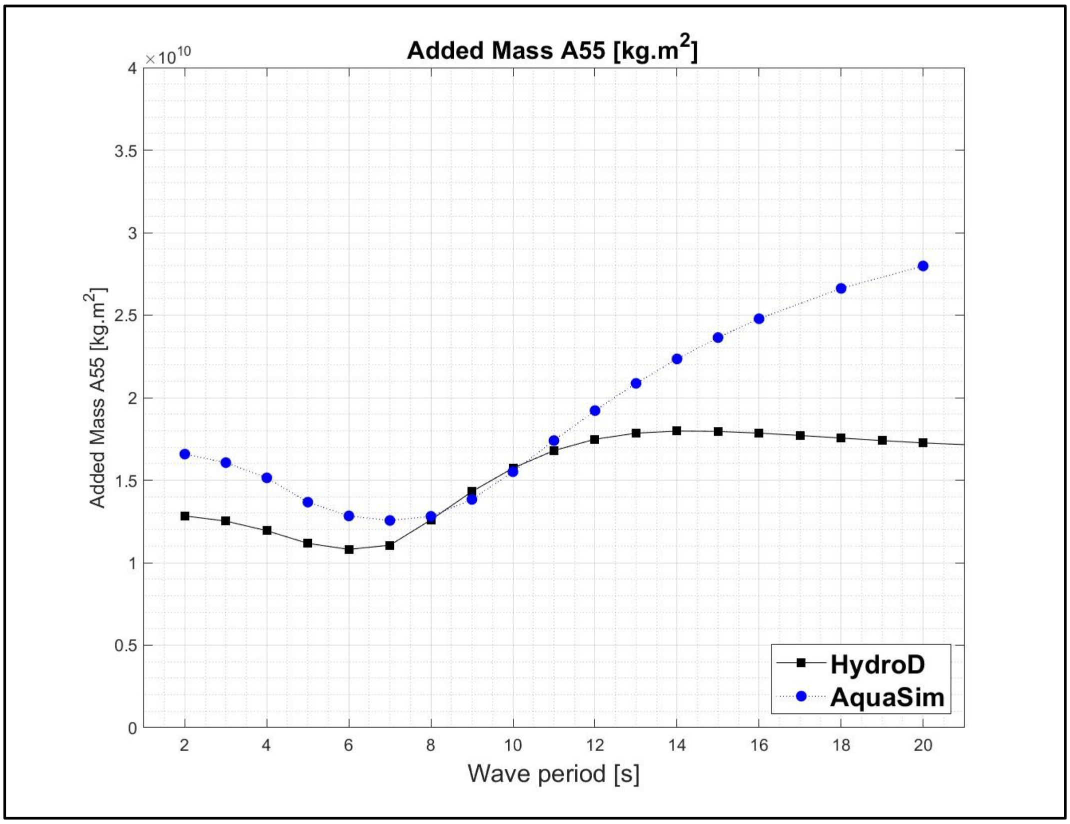


Figure 25: Comparison of added mass A55 by different approaches.

Motion Response of Ring Floater

Ring Floater Description

A general view of the ring floater is shown in Figure 26. A close view of the ring floater model is shown in Figure 27. The following five components are included:

- Component (RingPontoonStiffness): Beam Element, in section Component (RingPontoonStiffness);
- Component (FloaterRingPontoon): Membrane Element, in section Component (FloaterRingPontoon);
- Component (RingPontoonFrames): Beam Element, in section Component (RingPontoonFrames);
- Component (ConnectFrames): Beam Element, in section Component (ConnectFrames);
- Component (MooringLines): Truss elements, the same section properties in section Component (MooringLines).

In section Explanation about Local Connections, the connection between different components is explained. Vertical bending moment and horizontal bending moment are measured for RingPontoonStiffness, described in section Component (RingPontoonStiffness).

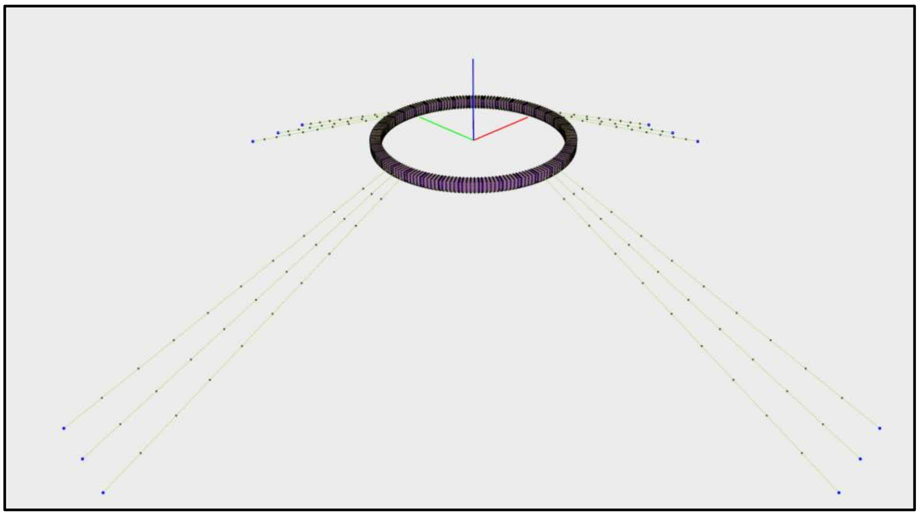


Figure 26: Global view of ring pontoon model.

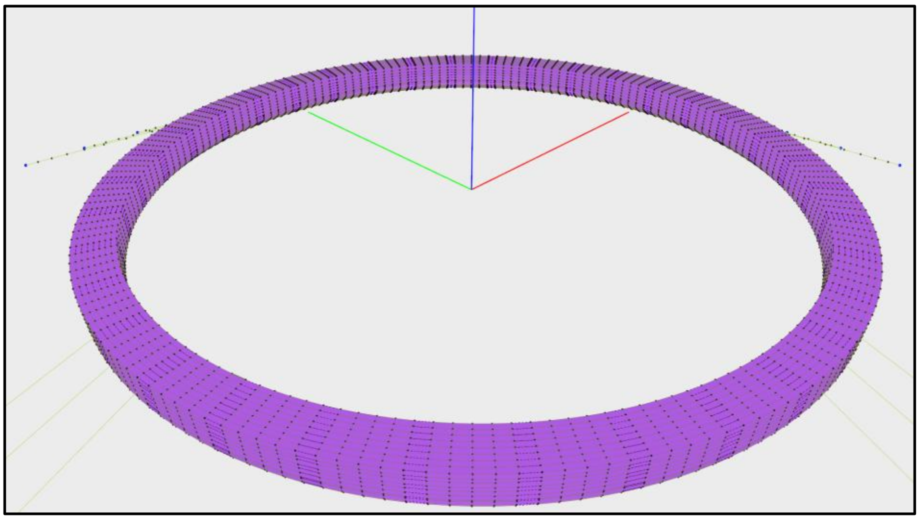


Figure 27: Close view into ring pontoon model.

Component (RingPontoonStiffness)

Illustrated in Figure 28 and Figure 29, the global stiffness of the ring pontoon is modelled as beam sections. Global vertical and horizontal bending moments can be measured from those beams. Section stiffness properties and hydrodynamic properties are shown in Figure 30 and Figure 31. This beam is not supposed to withstand hydrodynamic loads, but shall contribute to the global stiffness.

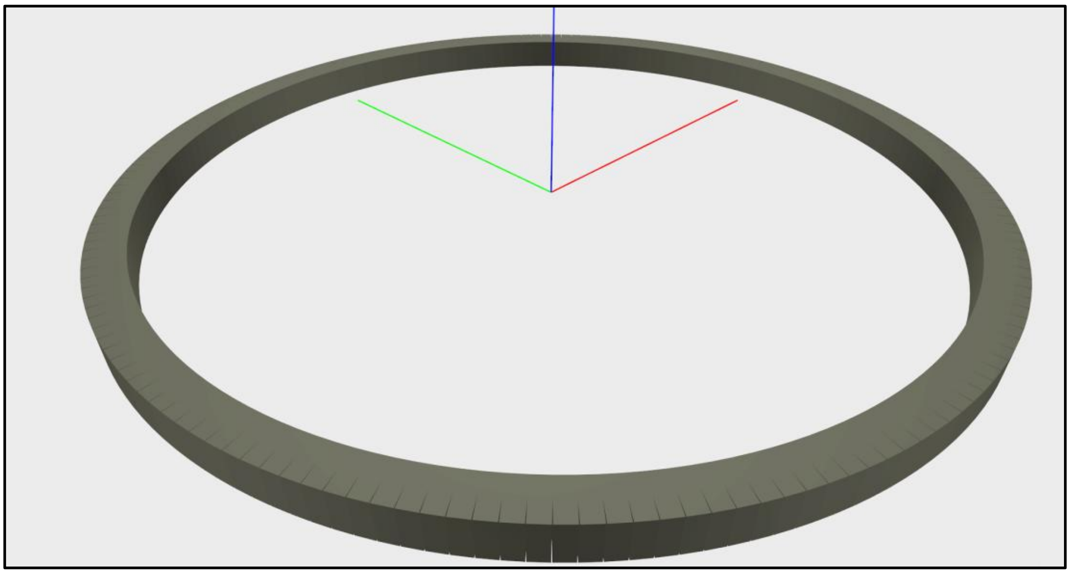


Figure 28: Component (RingPontoonStiffness): global stiffness for ring pontoon with cross section profile.

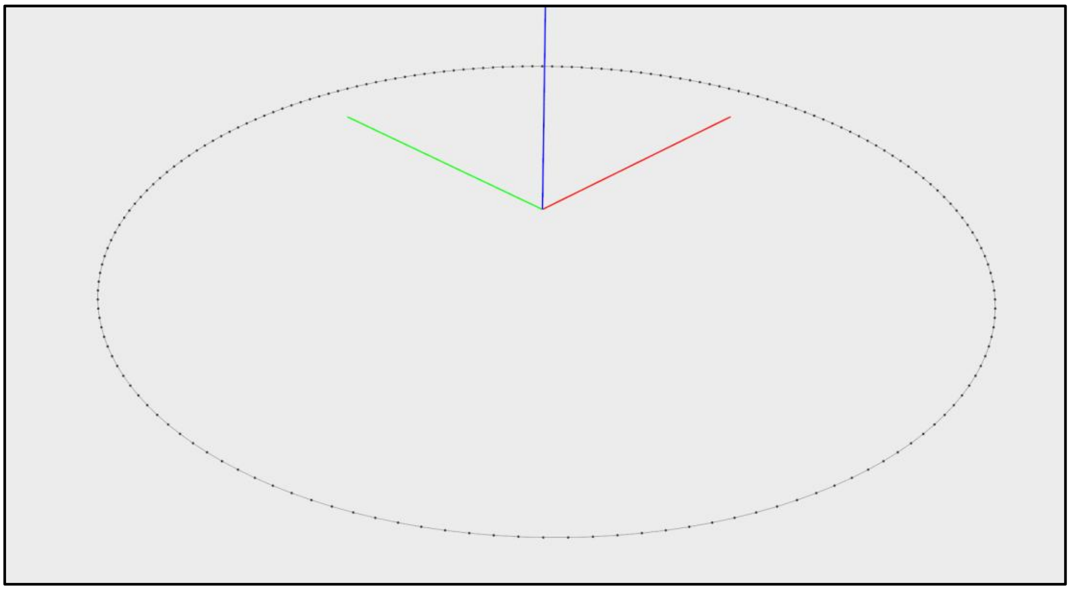


Figure 29: Component (RingPontoonStiffness): global stiffness for ring pontoon without cross section profile.

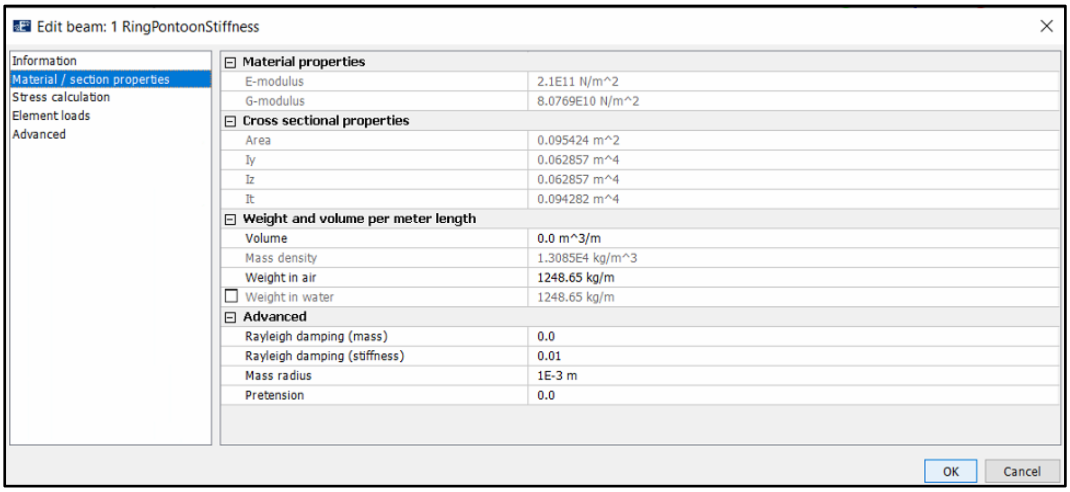


Figure 30: Material properties for component (RingPontoonStiffness).

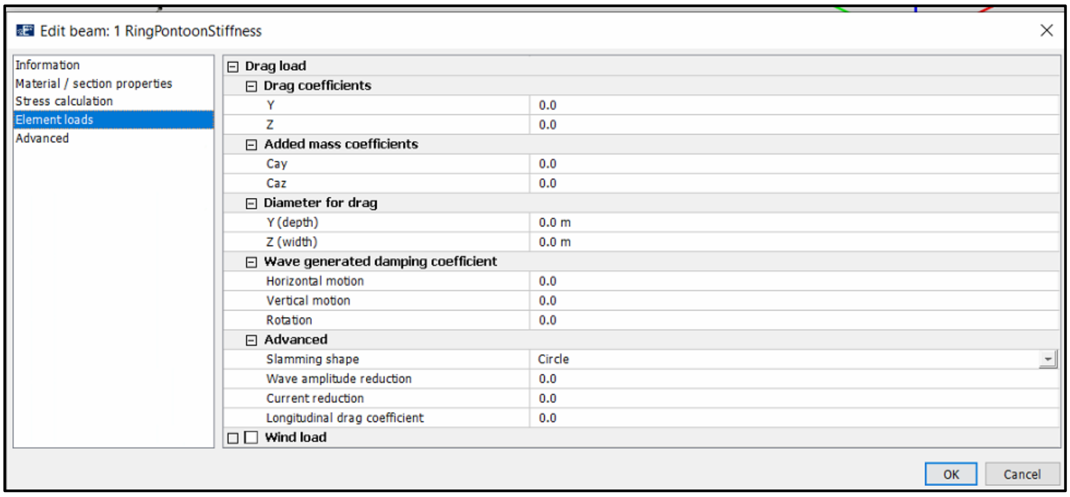


Figure 31: Hydro properties for component (RingPontoonStiffness).

Component (FloaterRingPontoon)

Membrane elements for component (FloaterRingPontoon) are shown in Figure 32. The membrane elements are connected with component (RingPontoonFrames) by sharing the same nodes.

Compared with the Barge model in section Barge Model Description, water is entrapped by the ring floater and sloshing modes exist inside the ring pontoon. The interaction between ring pontoon segments can influence diffraction and radiation.

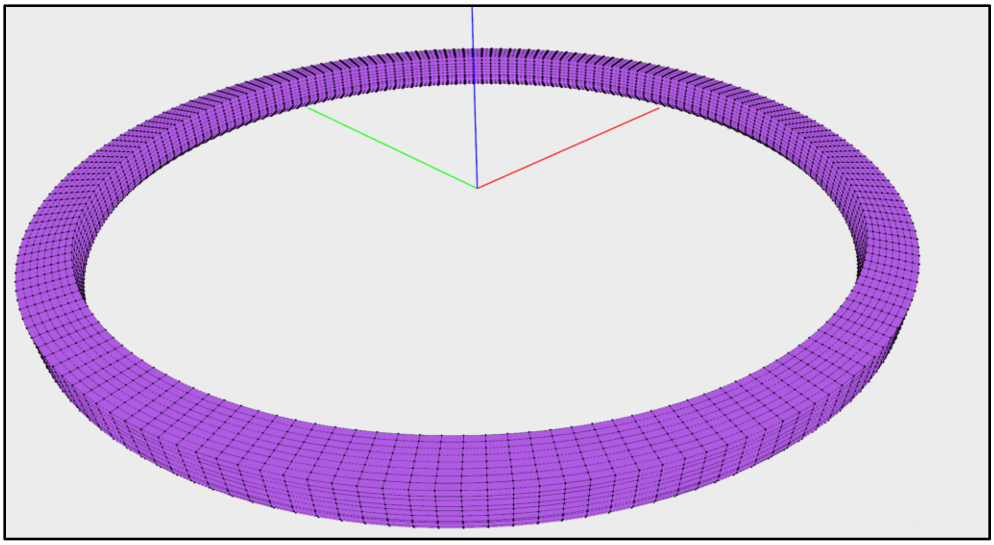


Figure 32: Membrane element for component (FloaterRingPontoon).

Component (RingPontoonFrames)

As shown in Figure 33 and Figure 34, the ring pontoon is divided into 36 separate modules. The purpose of component (RingPontoonFrames) is to provide stiffness for the membrane elements. These beams are designed to have stiffness and will not take hydrodynamic loads.

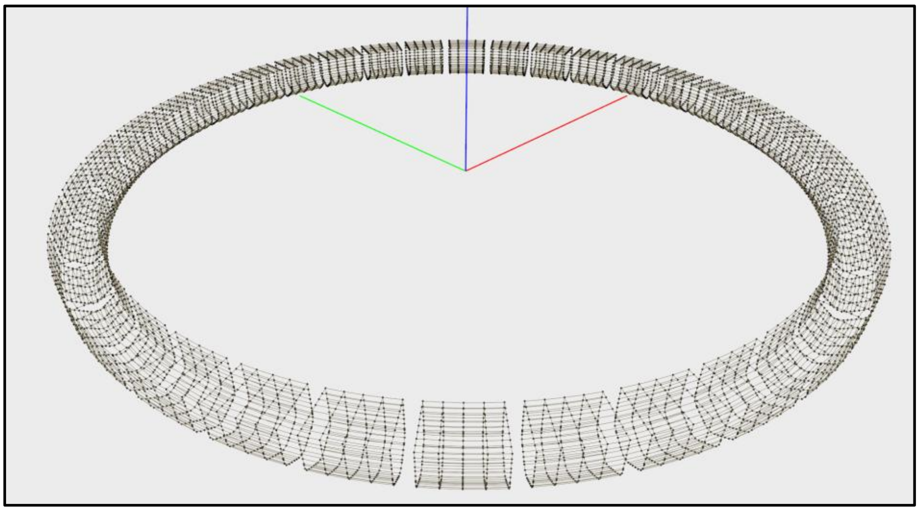


Figure 33: General view of component (RingPontoonFrames).

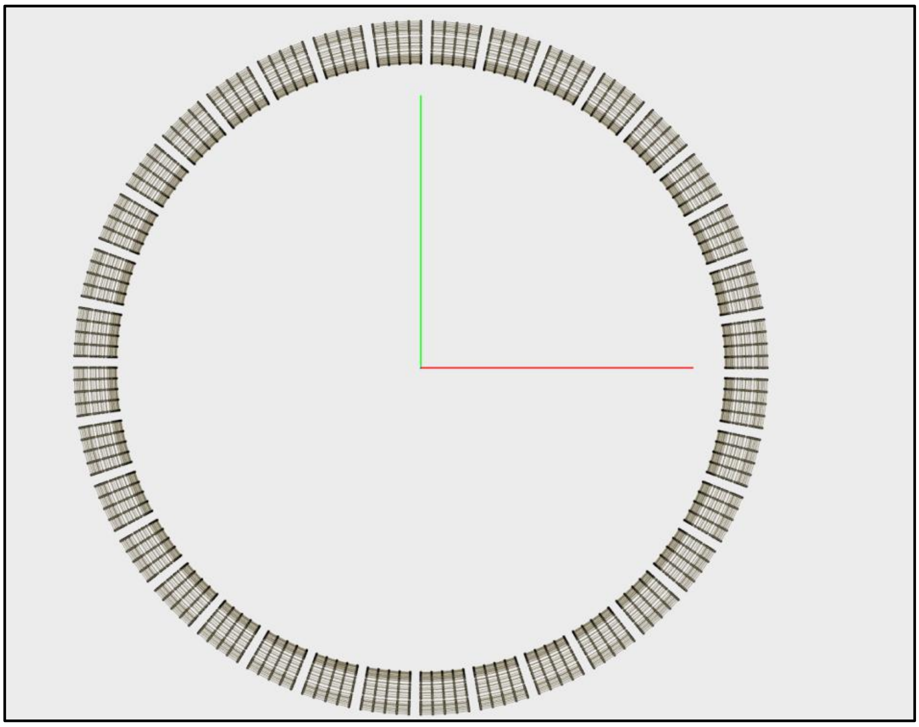


Figure 34: Top view of component (RingPontoonFrames).

Component (ConnectFrames)

The component (ConnectFrames) is used to connect the component (RingPontoonFrames) to the component (RingPontoonStiffness). As shown in Figure 33 and Figure 34, the total ring floater can be divided into 36 modules. For each module, two frames are used to connect with the component (RingPontoonStiffness).

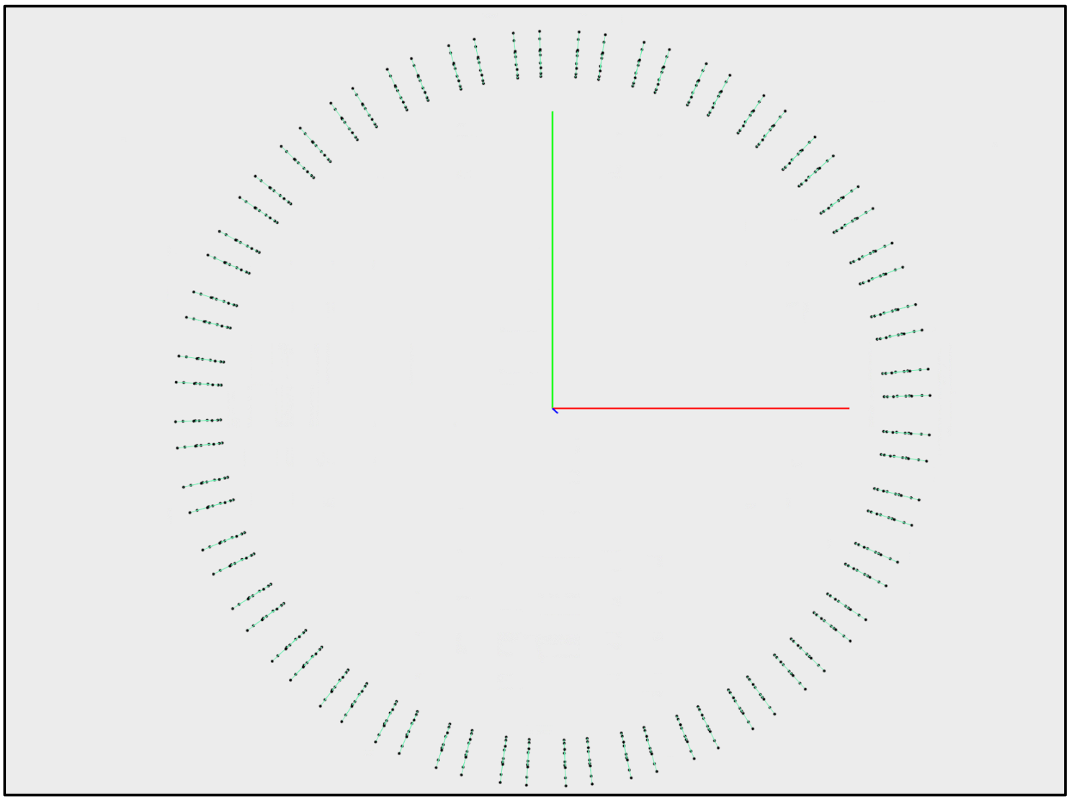


Figure 35: ConnectFrames beam, which connect component (RingPontoonFrames) to component (RingPontoonStiffness).

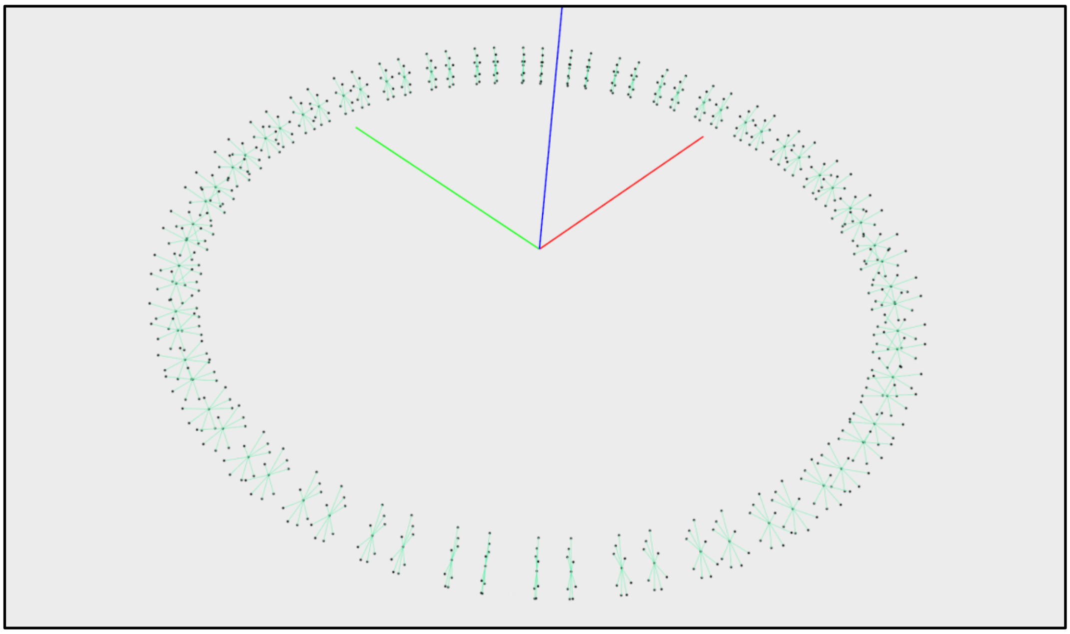


Figure 36: ConnectFrames beam, which connect component (RingPontoonFrames) to component (RingPontoonStiffness).

Explanation about Local Connections

Figure 37 further illustrates how different components are connected:

- Component (FloaterRingPontoon) is connected to component (RingPontoonFrames) by sharing the same nodes.
- Component (RingPontoonFrames) is connected to component (RingPontoonStiffness) by component (ConnectFrames)

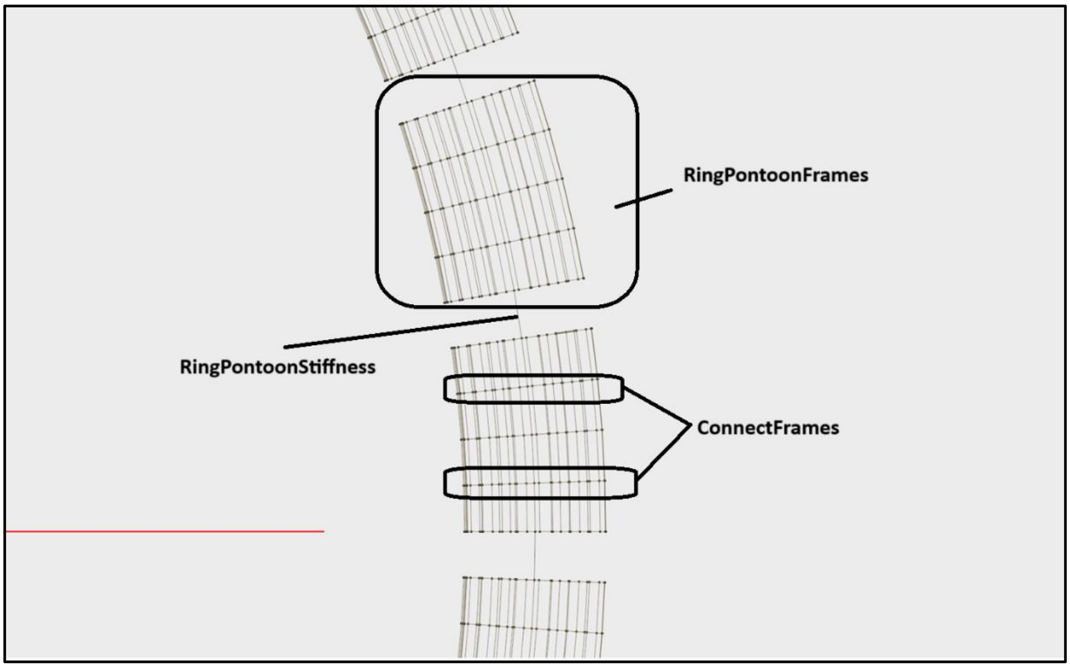


Figure 37: Illustration of connection among different components.

Added Mass and Damping Comparisons

Figure 38 compare the added mass A11 and A33 between “AquaSim” and “HydroD”. Figure 39 compare the damping B11 and B33 between “AquaSim” and “HydroD”. AquaSim shows identical results with HydroD. Slight difference is due to that HydroD use dense mesh and HydroD give results based on “potential formulation”. AquaSim is based on “source formulation”. Slight difference in added mass and damping are to be expected depending on whether they are calculated based on “potential formulation” or “source formulation”.

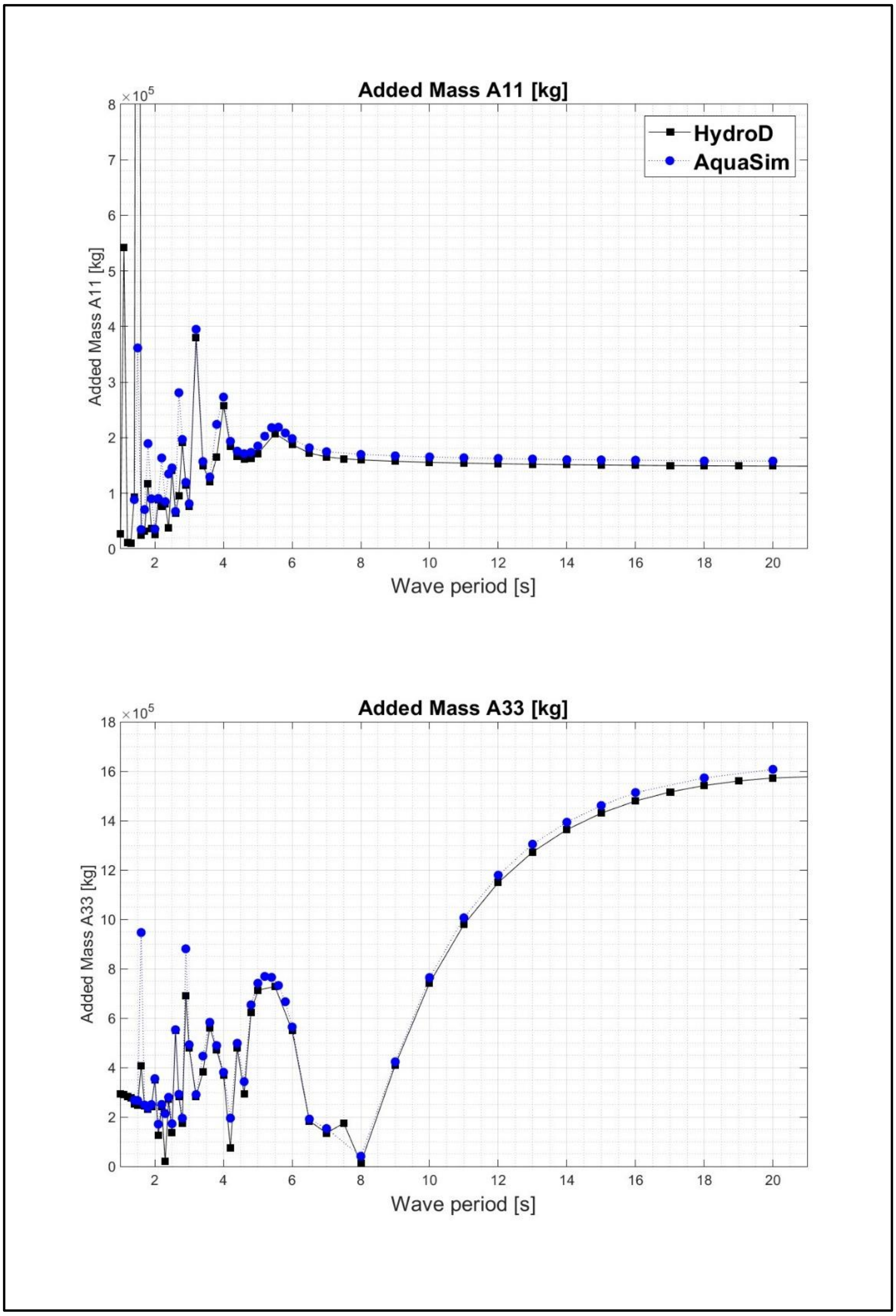


Figure 38: Comparison of added mass A11 and A33.

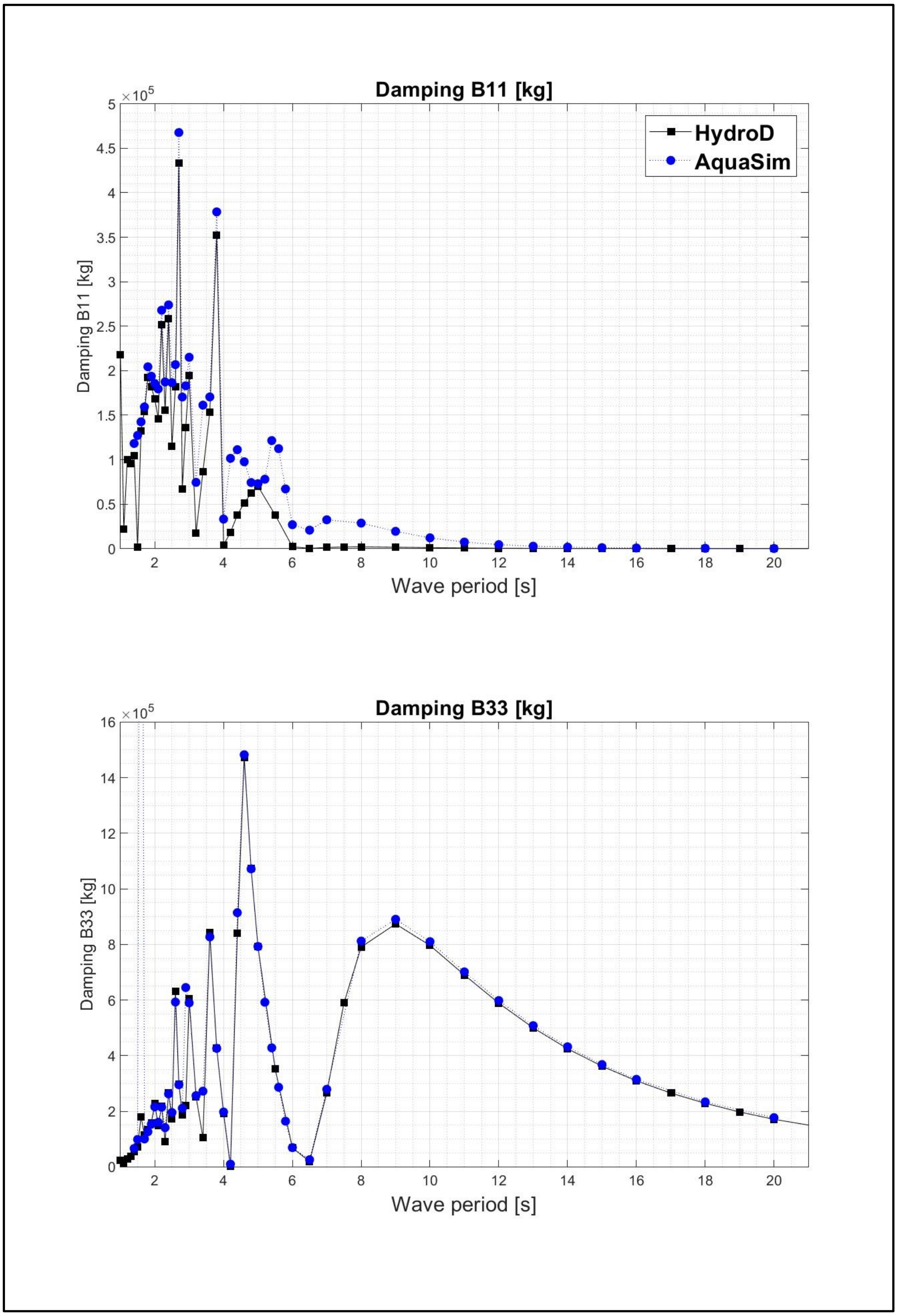


Figure 39: Comparison of damping B11 and B33.

Motion Response Comparisons

AquaSim time domain simulations are to be carried out under two sets of regular wave heights of 0.5m and 2.0m. Surge, heave, and pitch motion amplitudes are to be compared with frequency domain results from WADAM. For pitch motion, the response for periods from 6.0s to 12.0s show noticeable differences, and also nonlinear effects influence the pitch amplitude, as expected. The reason for the difference is mainly due to that A55 and B55 are calculated from different methods in AquaSim and WADAM.

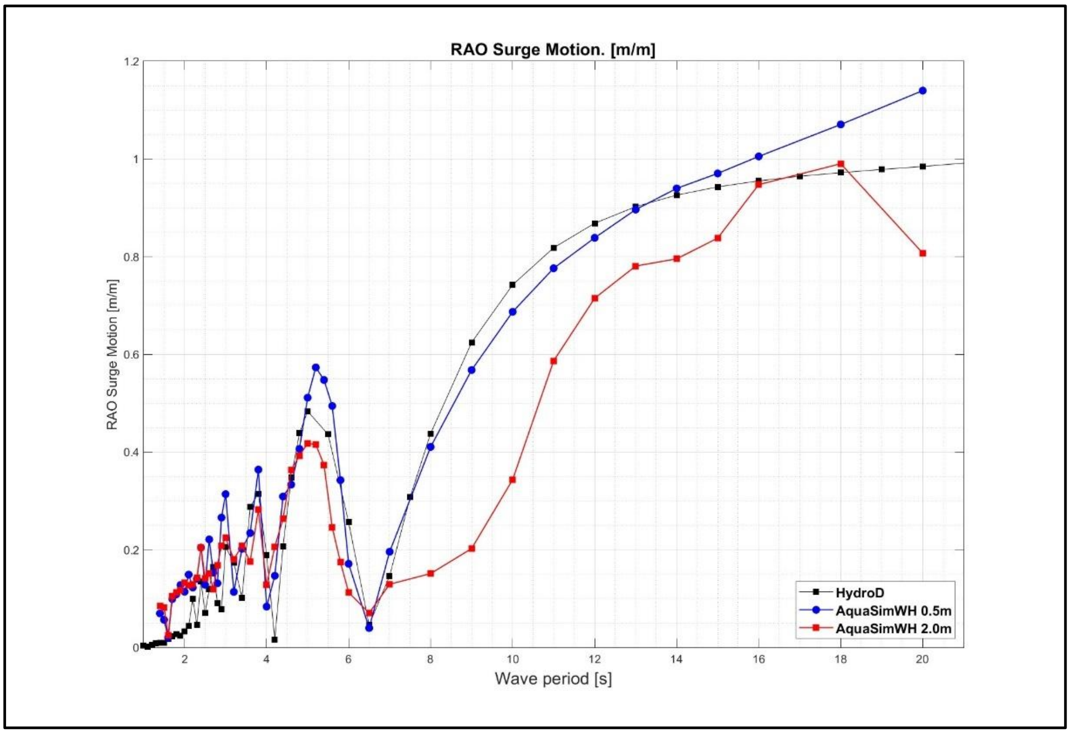


Figure 40: Comparison of surge motions.

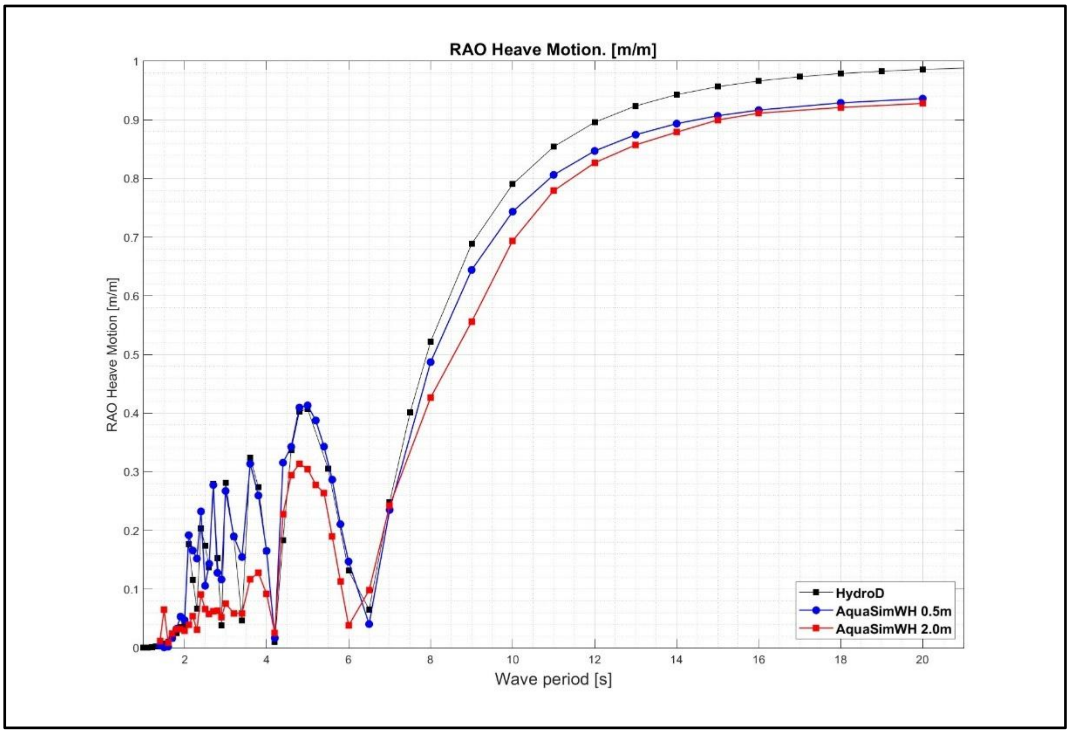


Figure 41: Comparison of heave motions.

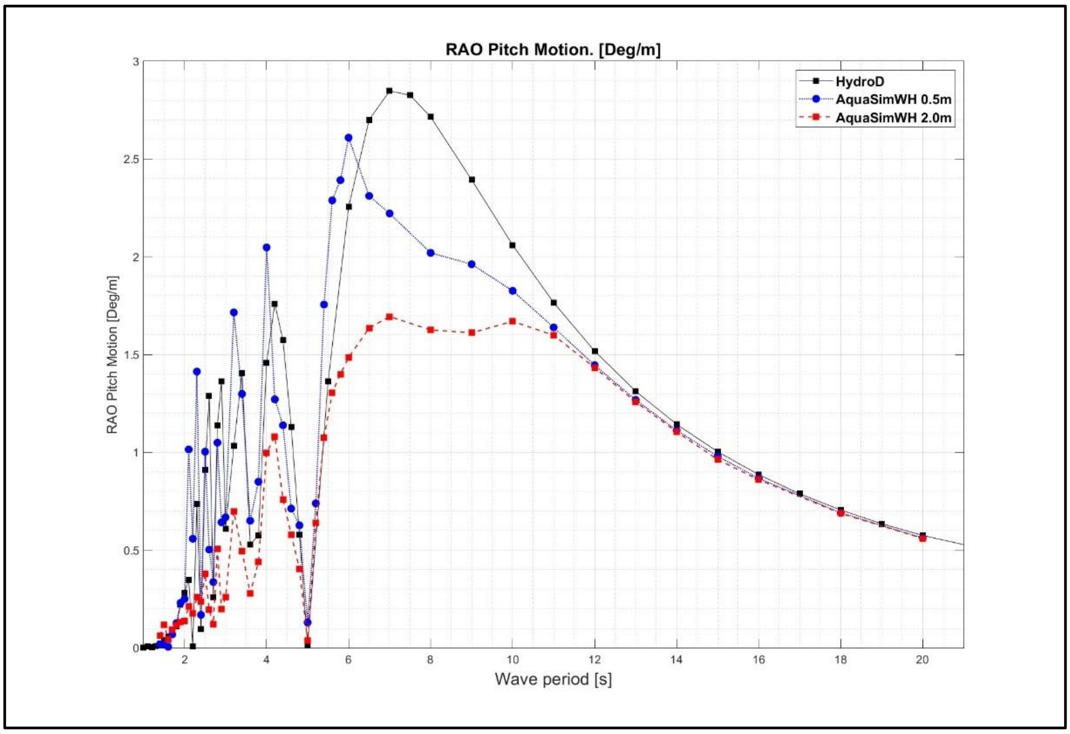


Figure 42: Comparison of pitch motions.

Sectional Loads Comparisons

Similar to the results in section Motion Response Comparisons, vertical bending moment and horizontal bending moment, illustrated in Figure 43, are compared in Figure 44 and Figure 45. For horizontal bending moments, AquaSim results agree well with the frequency domain results from HydroD. For the vertical bending moment, the vertical bending moment is lower in AquaSim, and this is because the pitch motion is also lower in AquaSim compared to HydroD.

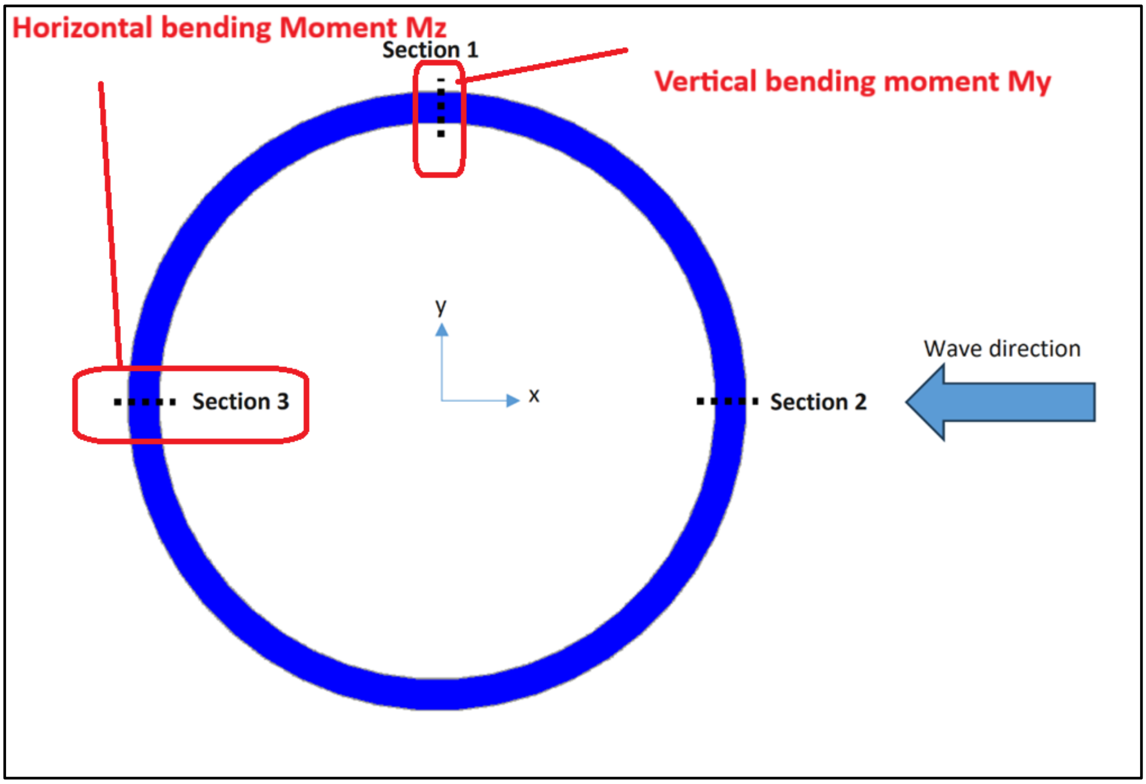


Figure 43: Illustration of transverse sections where vertical bending moment and horizontal bending moments are measured.

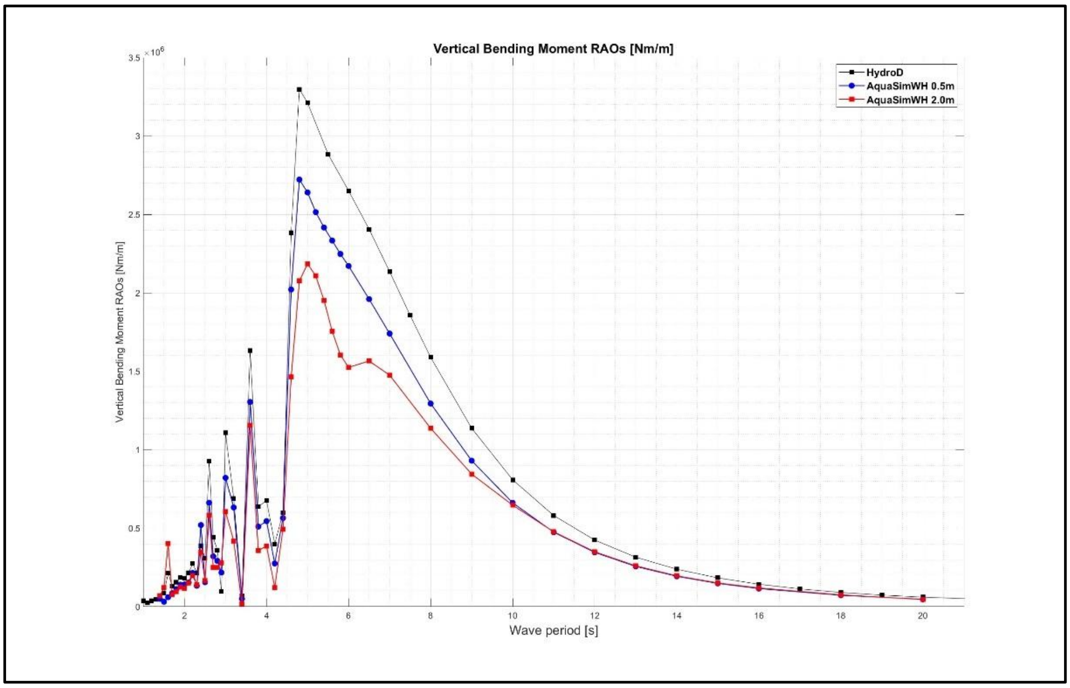


Figure 44: Comparison of vertical bending moment My.

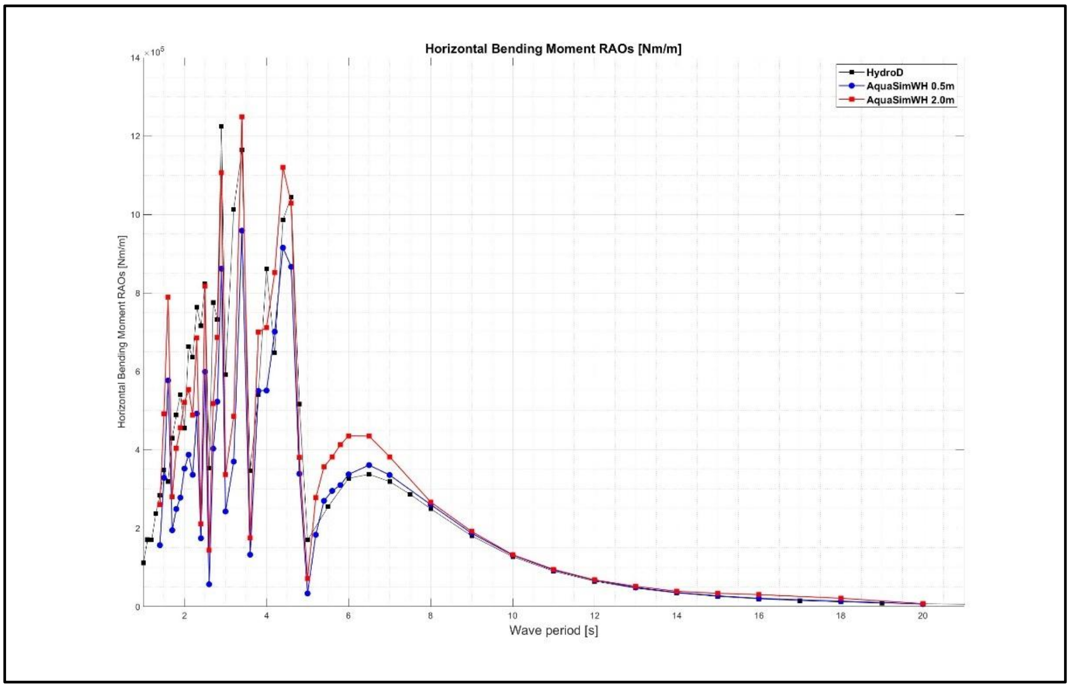


Figure 45: Comparison of horizontal bending moment Mz.

Comparisons of Added Mass A55

Under the heave mode, the added mass A33 is assumed to be evenly distributed over the wetted surface due to symmetry. In AquaSim, the term added mass A55 can be calculated by the integration of added mass A33. Comparisons of added mass A55 is shown in Figure 46. The added mass A55 in HydroD is calculated from pitch mode. The added mass A55 from AquaSim is calculated based on the added mass A33 under heave mode.

From the comparison, it can be observed that the equivalent added mass A55 shows noticeable differences compared with WADAM. This explains the difference in calculated pitch motions.

Compared with the barge model, the interaction between different segments in the ring pontoon is more significant. Consequently, the motion response and sectional loads calculated by AquaSim show certain differences compared with the results from WADAM.

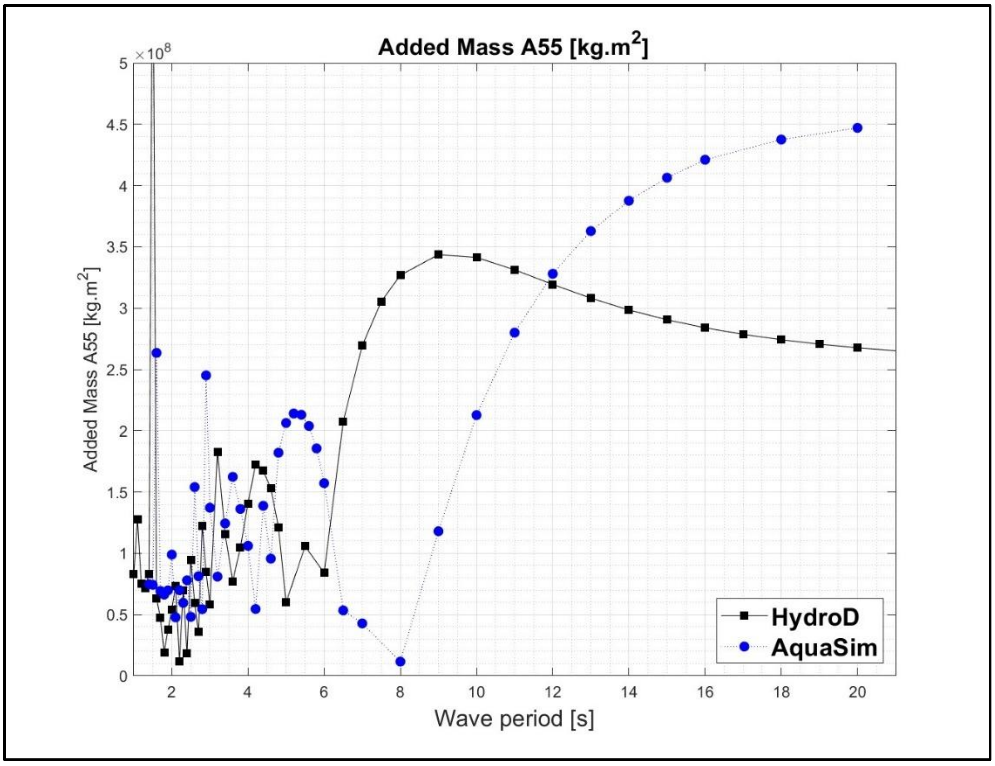


Figure 46: Comparison of added mass A55 by different approaches.