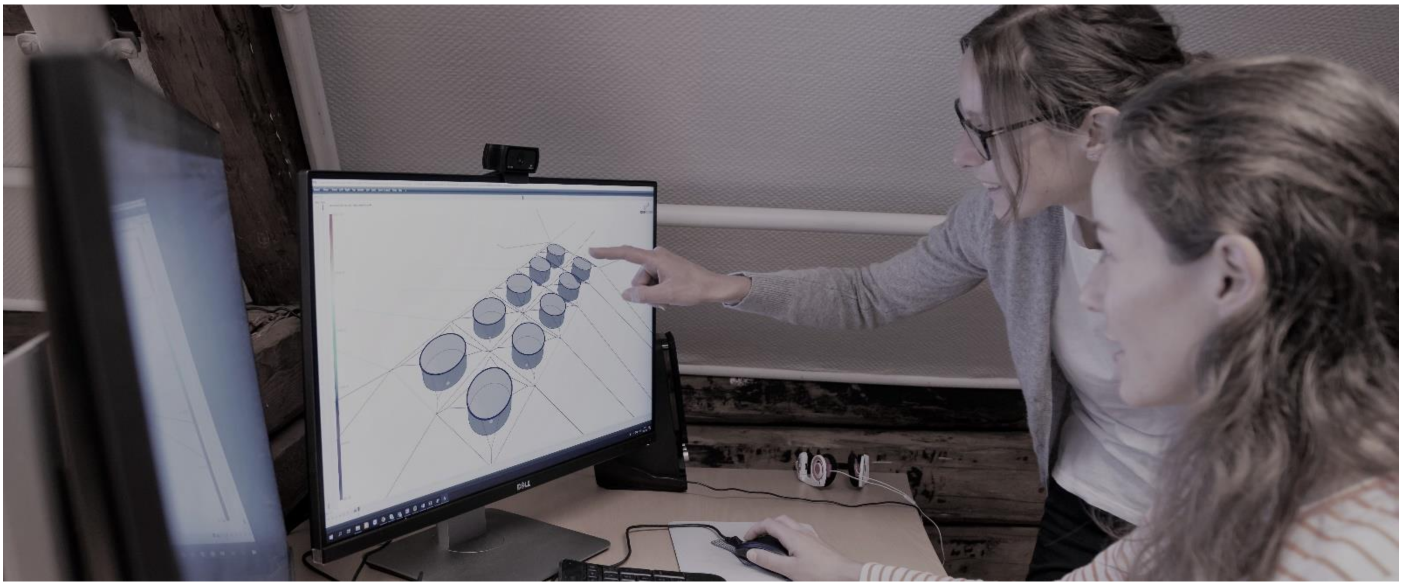
AquaSim training courses

- **Wave loads on lice skirt**



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Content

1 Prerequisites

The tutorial presents a simple case study with the purpose of demonstrating functionality in AquaSim.

It is assumed that the user is familiar with the basic principles of modelling and specifying material parameters in AquaEdit, as well as conducting analyses. If you are looking for an introduction to AquaSim we advise you to start with the Basic program tutorials.

2 Introduction

This tutorial describes how wave loads on impermeable net, such as lice skirts, are defined and analysed in AquaSim. Focus is on the "Wave excitation load"-part of the load interface found in AquaEdit. Particular attention is paid to the "Flexible tarp" load formulation and how it can be combined with numerical diffraction in the hybrid load model. The purpose is to provide a step-by-step introduction to the formulation, its theoretical basis, and its practical implementation in AquaSim.

Fundamental principles are presented first, including Froude-Kriloff pressure and wave particle kinematics, and how these are applied to flexible impermeable nets. Example analyses are presented to illustrate the approach, followed by comparisons with analytical solutions and physical model test data.

The overall aim is to give the user an understanding of how lice skirts, and similar impermeable nets, respond to waves and currents, and how AquaSim's hybrid load model can be applied.

3 Definitions regarding diffraction loads to impermeable nets

Lice skirts are modelled in AquaSim by applying the Lice skirt load formulation to membrane panels, as illustrated in Figure 1.

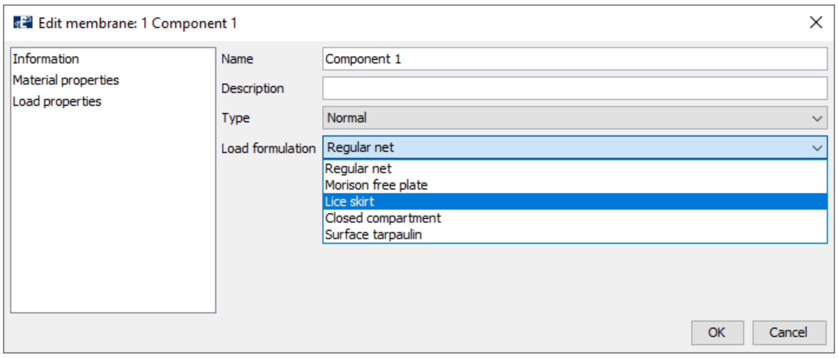

Figure 1 Lice skirt load formulation in AquaEdit

It should be noted that both waves and current contribute to loads from the drag coefficients, as outlined in the tutorial *Lice skirt with current* (Aquastructures AS, 2025a), since total velocity on the membrane panel is given by:

$$U = U_c + U_w - U_s$$

where

- U is total velocity,
- U_c is fluid velocity from current,
- U_w is fluid velocity from wave motions,
- U_s is the velocity of the membrane panel.

The magnitude of these loads is determined by the drag coefficients as presented in Figure 2.

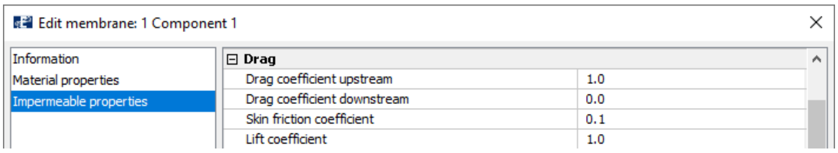

Figure 2 Drag coefficients for Lice skirt load formulation

Drag loads are calculated from the incident wave field and come in addition to the wave excitation loads.

3.1 Hydrodynamic forces and load formulations

The aim of this section is to provide a short overview of the forces that arise on structures exposed to waves, to make the user capable of seeing the relation between input in AquaSim and its load formulations. Hydrodynamic loads in regular waves can be categorized into two main types: *wave excitation* loads and *radiation* loads.

$$F_{Hydro} = F_{EXC} + F_{RAD}$$

where F_{EXC} is the wave excitation loads and F_{RAD} is radiation.

1. **Wave excitation loads** originate from waves that impact a structure and are composed of *Froude-Kriloff* force (F_{FK}) and *diffraction* force F_{DIFF}:

$$F_{EXC} = F_{FK} + F_{DIFF}$$

2. **Radiation loads** originate from the structure moving due to waves, and are normally expressed in terms of added mass and damping:

$$F_{RAD} = -F_{AddedMass} - F_{Damping}$$

AquaSim provides several load formulations to calculate these forces, adapted for different types of structures and load scenarios. The next sections will elaborate on how the different load formulations work.

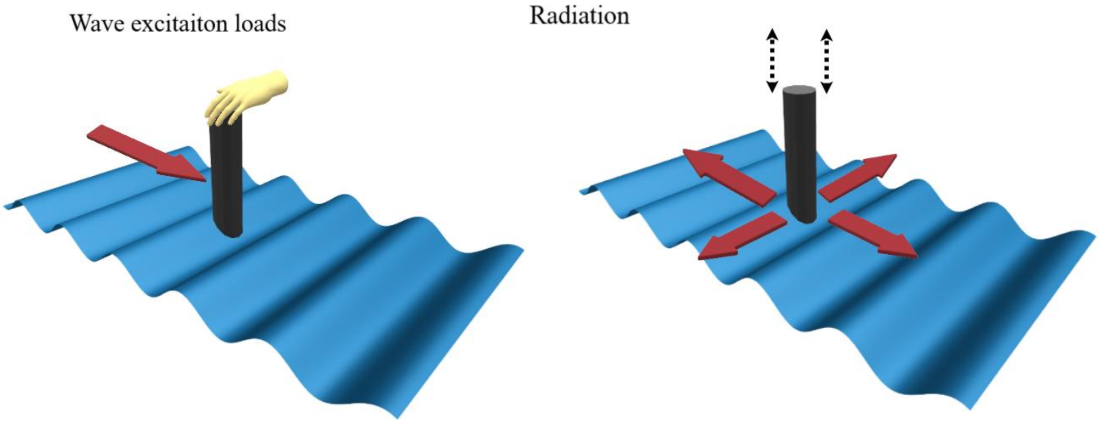

Figure 3 Wave excitation loads (structure restrained) and Radiation (structure forced to move)

3.2 Wave excitation load formulations in AquaSim

Focus will be on the parameters found in the "Wave excitation load" section under Impermeable properties in AquaEdit (see Figure 4). Special attention is on "Flexible tarp" load formulation and its associated parameters (see Figure 5).

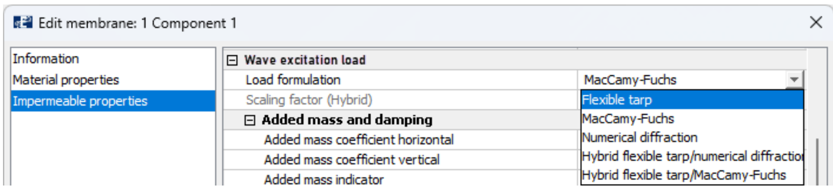

Figure 4 Diffraction properties for Lice skirt in AquaEdit

Associated parameters for Flexible tarp covers added mass and damping.

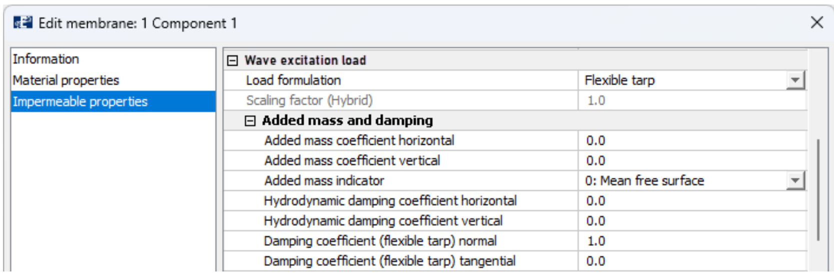

Figure 5 Diffraction parameters

AquaSim has several load formulations to calculate wave excitation forces, these are shortly presented in Table 1.

Table 1

Aspects	**Flexible tarp**	**MacCamy-Fuchs**	**Numerical diffraction**	**Hybrid flexible tarp/ Numerical diffraction**	**Hybrid flexible tarp/ MacCamy-Fuchs**
Theory	Adapted for flexible woven textiles. Follows wave fluid particle motion.	Adapted for rigid structures. Apply theory from (R. MacCamy, 1954). Apply Bessel functions to model diffraction effects.	Numerical method NEMOH (A. Babarit, 2015) applied to calculate. Surface is discretized to calculate velocity potential (potential theory).	Combination of Flexible tarp- and Numerical diffraction methods. The methods are weighted through "Diffraction scaling".	Combination of Flexible tarp- and MacCamy-Fuchs methods. The methods are weighted through "Diffraction scaling".
Load terms included	Froude-Kriloff pressure.	Froude-Kriloff pressure and diffraction.	Froude-Kriloff pressure, diffraction, added mass and damping.	Weighted fraction of Froude-Kriloff (Flexible tarp) and Froude-Kriloff, diffraction, added mass and damping (Numerical diffraction).	Weighted fraction of Froude-Kriloff (Flexible tarp) and Froude-Kriloff and diffraction (MacCamy-Fuchs)
Limitations	Diffraction forces are omitted. Hence, this formulation is not suitable for rigid structures stand alone. Loads may be	Fully rigid structures. Solves wave potential around a fixed, bottom mounted vertical cylinder	Handles complex geometries and multi-body interactions at finite water depth more flexible	Accuracy depends on the structures rigidity/ flexibility and chosen scaling factor to	Accuracy depends on the structures' rigidity/ flexibility and chosen scaling factor to

	underestimated if applied structure is rigid. With option of adding radiation (added mass and damping) separately.	in finite water depth. With option of adding radiation (added mass and damping) separately.	compared with analytical methods. Radiation forces are found automatically, meaning added mass- and damping coefficients works as scaling factor. Factors of 1.0 means the proposed solution from NEMOH is applied.	weight the two methods.	weight the two methods. With option of adding radiation (added mass and damping) separately.
Linear/ nonlinear	Linear but includes the nonlinear effect arising from in and out of water. Option to add the nonlinear velocity term in Bernoulli which means that the terms for calculation of mean drift are included except from the velocities originating from radiation. .	Linear but includes the nonlinear effect arising from in and out of water, assuming small wave amplitudes and that fluid motion and pressure field vary linearly with wave amplitude. Corresponding option to add drift, as for Flexible Tarp.	Linear but includes the nonlinear effect arising from in and out of water, assuming linear waves. Corresponding option to add drift, as for Flexible Tarp.	Linear but includes the nonlinear effect arising from in and out of water. Corresponding option to add drift, as for Flexible Tarp.	Linear but includes the nonlinear effect arising from in and out of water. Corresponding option to add drift, as for Flexible Tarp.
Implementation	Analytical formulas	Analytical, closed form series	Numerical results calculated from NEMOH.	Analytical (Flexible tarp) and numerical (Numerical diffraction)	Analytical
Typical areas of application	For highly damping-dominated structures such as lice skirts, tarpaulins, tubes and so.	Stiff vertical cylinders, monopiles, other stiff floating containers.	Large volume structures, rigid bodies such as pontoons, barges, cages.	Semi-flexible structures attached to rigid structures.	Semi-flexible circular structures.

4 The “Flexible tarp” load formulation

“Flexible tarp” load formulation stems from the recognition seen in tank testing, e.g. (Roaldsnes, 2020) that much of waves passed though the tarpaulin with little influence on the waves by the tarpaulin. It describes forces, added mass and damping on soft and flexible textiles can be modeled to resemble this. Characteristic for such structures, as lice skirts, is that a large part of the wave passes through more or less undisturbed, rather than scattering the waves as rigid bodies would.

The flexible tarp formulation is suitable for structures that are highly compliant, where they move with the water. This is called damping-dominated behavior where the structure’s response is mainly determined by how much the structure resist motion through damping.

4.1 Theoretical basis

As mentioned, wave excitation loads are composed of Froude-Kriloff and diffraction forces. Unlike rigid bodies, flexible textiles do not produce significant scattered waves, so the diffraction term is neglected. The "Flexible tarp" formulation is hence described only by the undisturbed Froude-Kriloff pressure. Following e.g. (Faltinsen, 1990) this pressure is described as:

$$p(x,z,t) = \rho g \zeta_A e^{kz} \sin{(kx - \omega t)}$$

Equation 1

where

- ρ is the density of seawater,
- g is the acceleration of gravity
- ζ_A is the wave amplitude,
- z is vertical location,
- k is wave number,
- x is location along x-direction,
- ω is wave frequency,
- t is time.

Presenting the horizontal fluid particle velocity due to waves:

$$u(x,z,t) = \omega \zeta_A e^{kz} \sin{(kx - \omega t)}$$

Equation 2

Now, consider a simple membrane panel in the yz-plane, as shown in Figure 6. This panel as an area A.

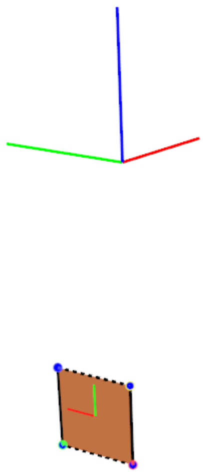

Figure 6 Simple membrane panel in yz-plane

Introduce this panel area to the equation for pressure (Equation 1) we get the Froude-Kriloff force:

$$F(x,z,t) = A \cdot \rho g \zeta_A e^{kz} \sin{(kx - \omega t)}$$

Equation 3

This is simply the undisturbed wave pressure field integrated over the structure's wetted surface.

4.2 Analysis

4.2.1 Froude-Kriloff pressure

The aim of this section is to present how the Froude-Kriloff pressure is calculated in AquaSim by establishing a simple model and compare analysis with analytical results. Consider a membrane panel with an area of $A = 4m2$. The panel is restrained with truss elements in each corner; this is illustrated in Figure 7.

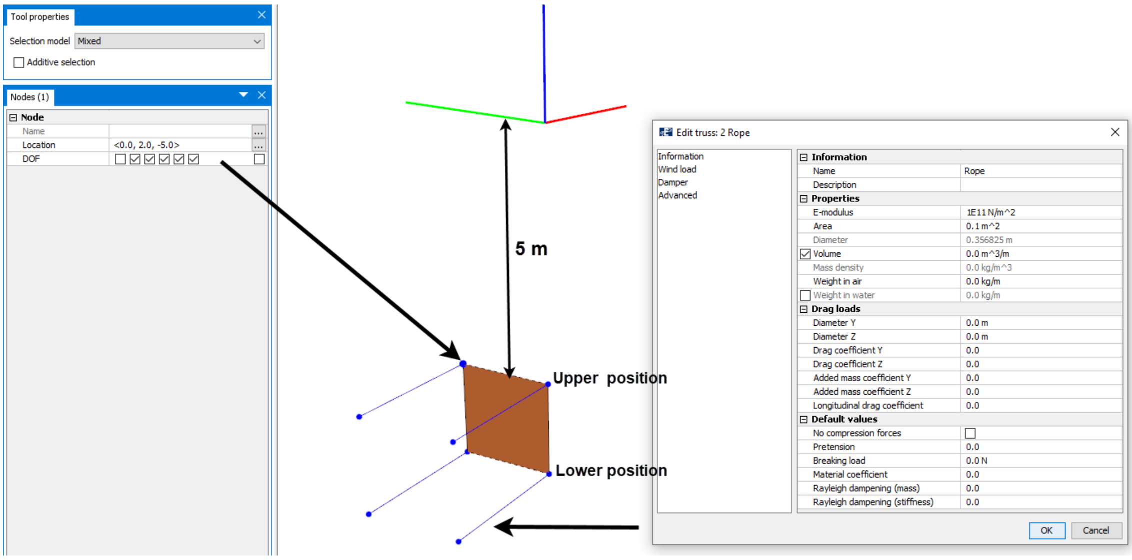

Figure 7 Analysis model

Each node on the panel is free to move along x-direction. Wave loads on the panel will be distributed as axial forces to the trusses. An analysis is carried out with wave data as presented in Table 2.

Table 2 Wave data applied to analysis

Parameter		Value
Wave amplitude, [m]	ζ_A	1
Density, [kg/m3]	ρ	1025
Period, [s]	t	100
Wave frequency, ,[1/s]	ω	6.28E-02
Wave number, [1/m]	k	4.02E-04
Position, z- upper [m]	z_{upper}	-5
Position, z- lower [m]	z_{lower}	-7
ekz- upper	$e^{kz_{upper}}$	0.99799
ekz- lower	$e^{kz_{lower}}$	0.997187
Pressure upper [N/m2]	p_{upper}	10035.04
Pressure lower [N/m2]	p_{lower}	10026.96

Since the panel area is 4m2, the forces in each truss should correspond to the pressure presented in Table 2. Figure 8 and Figure 9 show the resulting axial force from AquaSim in one of the upper trusses, and one of the lower. The upper truss takes up approximately 10034 N and the lower 10028 N. This corresponds well with the calculations in Table 2.

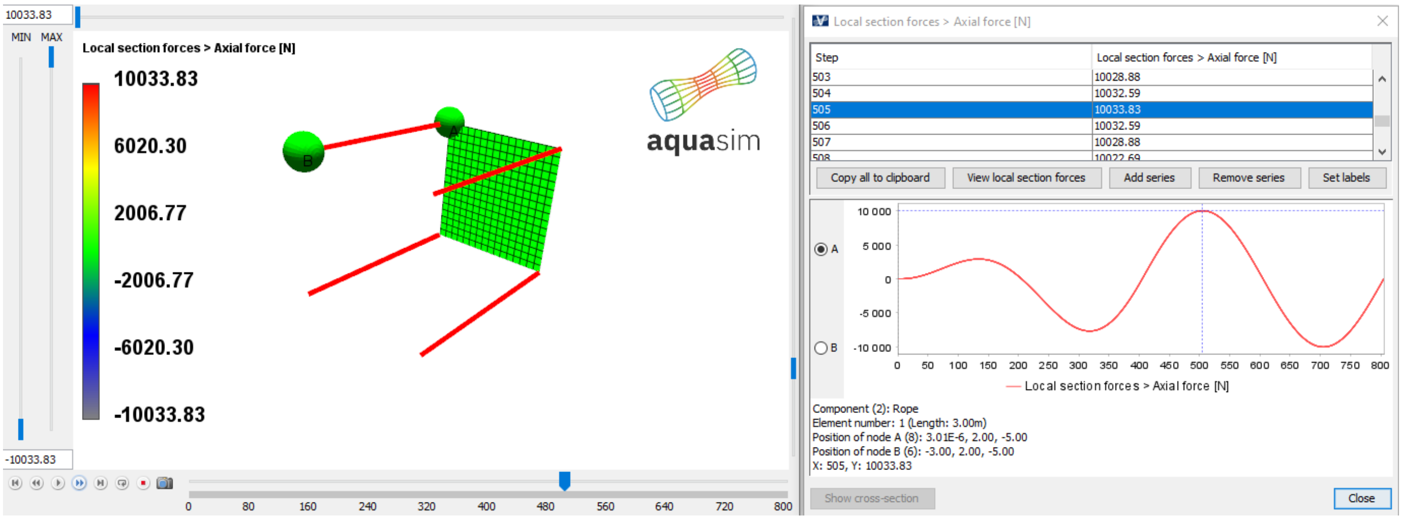

Figure 8 Axial force in upper truss

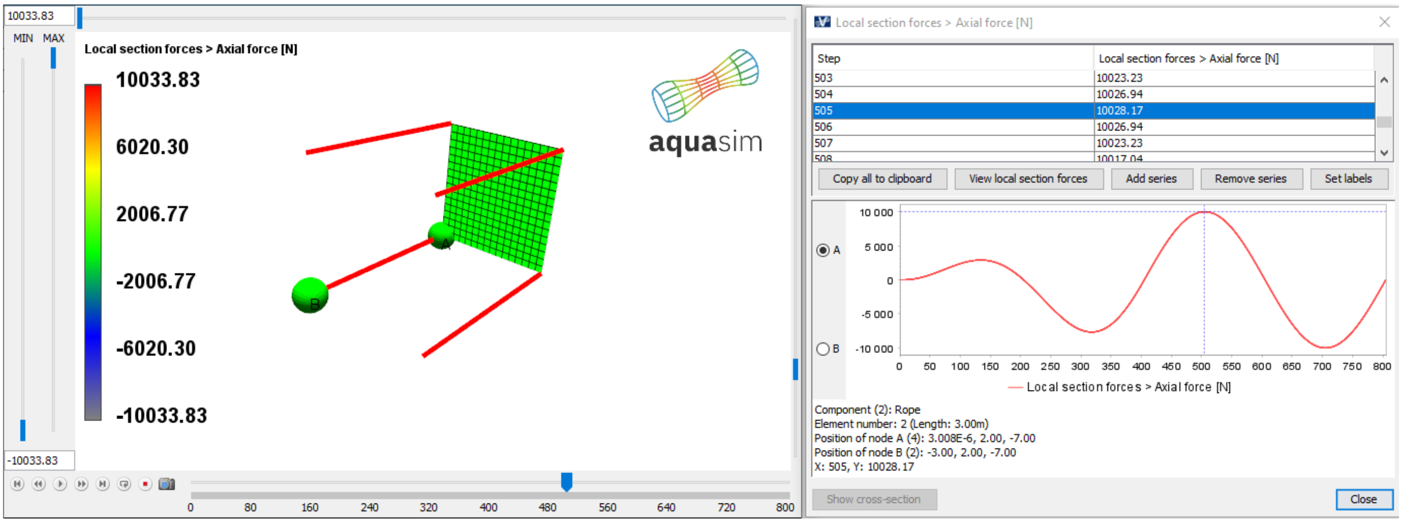

Figure 9 Axial force in lower truss

4.2.2 Horizontal panel response

The concept behind this section is to conduct an analysis to show that, in absence of any other external forces than the Froude-Kriloff pressure, the panel's motion should follow the wave particle motion of the surrounding fluid. This occurs when the Froude-Kriloff pressure is applied to the panel in the direction of the wave. To achieve this behavior, damping force F_D is introduced such that the resulting horizontal velocity of the panel u will match the wave particle velocity when subject to Froude-Kriloff pressure:

$$F_D \cdot u = F$$

where F is the Froude-Kriloff force. We then insert the expression for Froude-Kriloff force from Equation 3, and the horizontal fluid particle velocity from Equation 2, and get:

$$F_D = \frac{F}{u} = \frac{A \cdot \rho g \zeta_A e^{kz} \sin{(kx - \omega t)}}{\omega \zeta_A e^{kz} \sin{(kx - \omega t)}} = \frac{A \cdot \rho g}{\omega}$$

Equation 4

This means that if the damping term $\rho g/\omega$ is introduced to the membrane panel per m2, the response should follow the wave particle motion. In AquaSim, this corresponds to having the parameter "Damping coefficient (flexible tarp)" set to 1.0, see Figure 10.

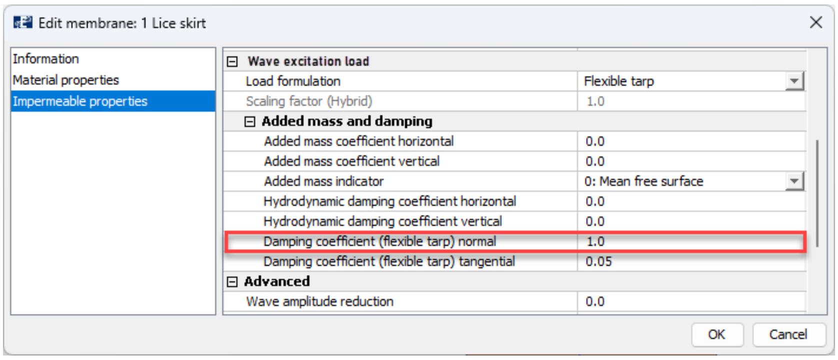

Figure 10 Parameter "Damping coefficient (flexible tarp)" set to 1.0

The damping force introduced to the membrane panel becomes:

$$F_D = \frac{Damping\ coefficient(flexible\ tarp) \cdot A\rho g}{\omega}$$

Equation 5

Go back to your model in AquaEdit. To enable the panel to move with the fluid particle motion, the trusses must be removed. They should not be deleted from the model, as this will lead to equilibrium not being found. We need the trusses so that the Froude-Kriloff pressure can be induced on the panel. Instead, we remove the trusses in the first dynamic step in the analysis by applying the Linebreake-function, see Figure 11. The panel is still free to move only in x-direction.

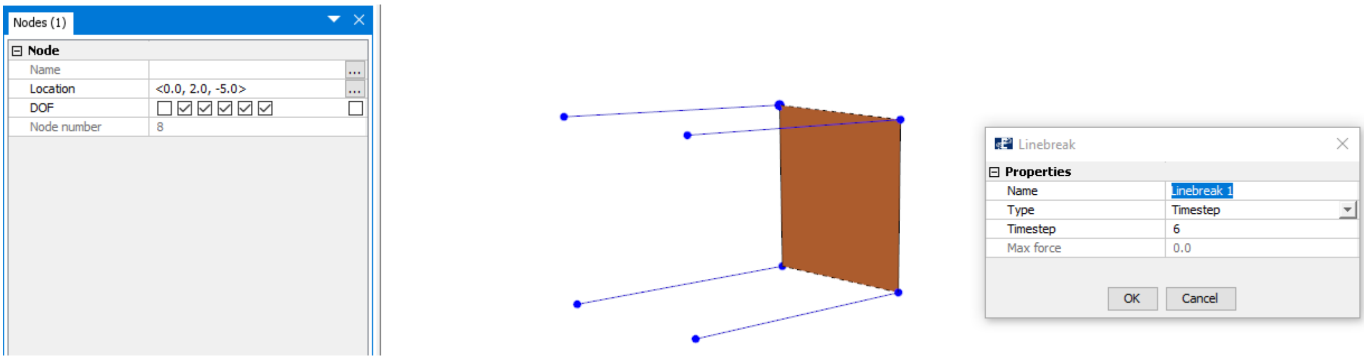

Figure 11 Linebreake introduced to truss elements. Panel is free to displace in x-direction

Analysis is run with the same wave parameters as presented in Table 2. The horizontal displacement of the panel is presented in Figure 12 and Figure 13. The results indicate that the panel follows the fluid particle motion as it has a sinusoidal response. Which is consistent with linear wave theory applied.

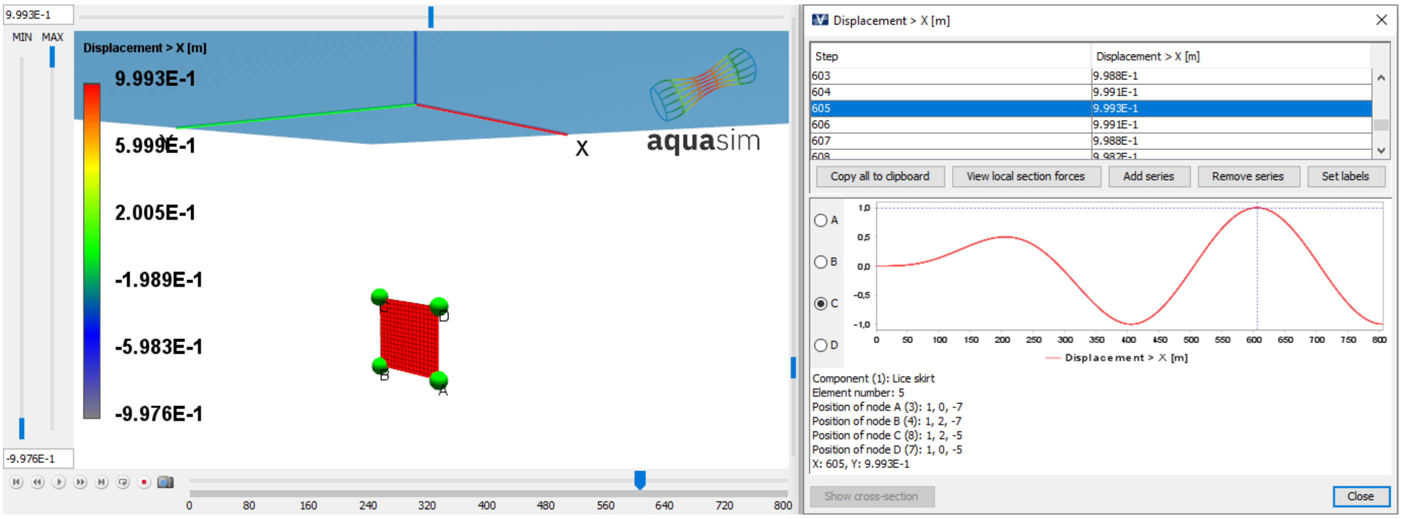

Figure 12 Displacement of node C (upper node)

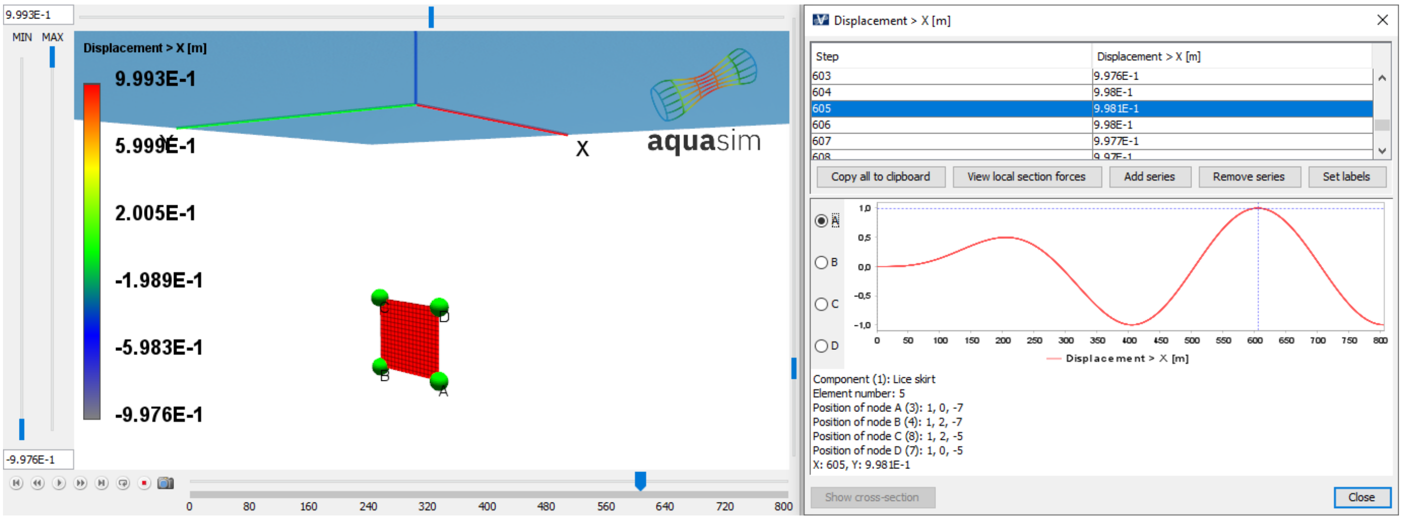

Figure 13 Displacement of node A (lower node)

When we consider distance to the water surface, for the same timestep as in Figure 12 and Figure 13, we see that the displacement is approximately 90 degrees after the wave elevation. This phase-relation is in line with the circular motion of the fluid particles.

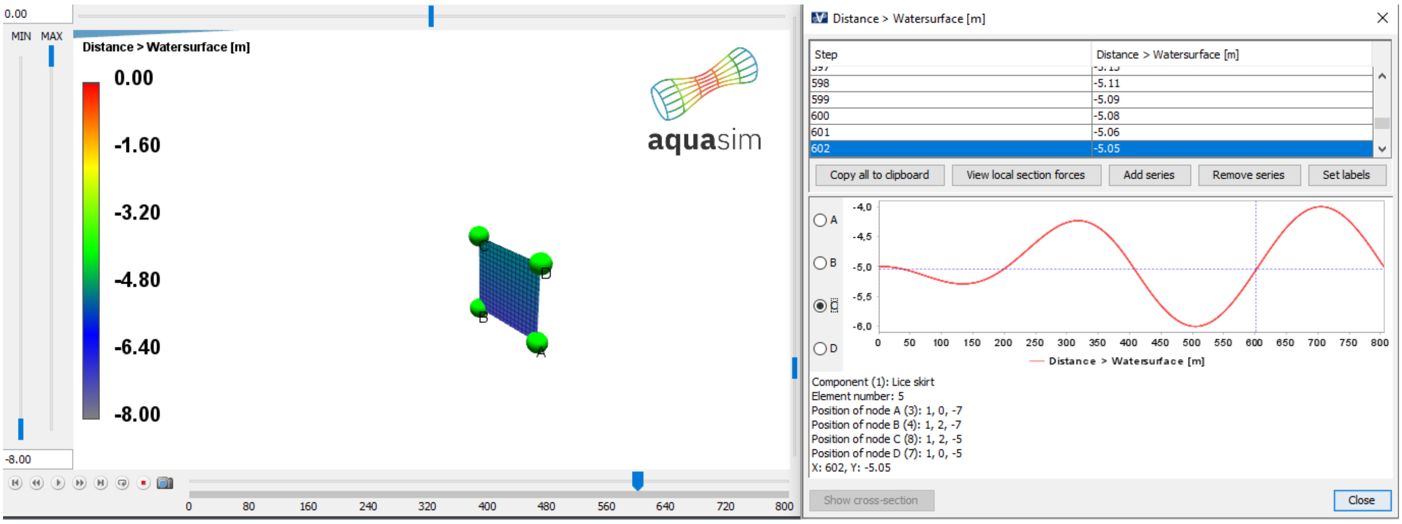

Figure 14 Distance to water surface for node C (upper node)

Horizontal displacement ξ of the panel is found by integrating the horizontal fluid particle velocity over time:

$$\xi(x,z,t) = \int u\,dt$$

where the maximum displacement is found as:

$$\xi_{MAX}(x,z,t) = \zeta_A \cdot e^{kz}$$

Equation 6

From Table 2 we know $\zeta_A = 1.0m$ and the upper node is located at $z_{upper} = -5m$ and the lower $z_{lower} = -7m$. This results in the displacement as presented in Table 3. Comparing AquaSim and analytical, the results fit well.

Table 3 Displacement of panel, analytical vs AquaSim

	Analytical	AquaSim
Displacement X, upper	0.9980	0.9981
Displacement X, lower	0.9972	0.997

4.2.3 Vertical panel response

In the vertical direction, the panel motion is in phase with both the pressure field and the wave surface elevation. This means that the relationship between vertical fluid motion and resulting panel response can be expressed in terms of an equivalent stiffness term. However, a stiffness term requires a defined reference position. So, it will be advantageous to handle the vertical direction by also using damping term as in Equation 5. The following algorithm is therefore applied to the vertical direction:

- A force equivalent to the Froude-Kriloff force is applied but shifted 90 degrees ahead of the Froude-Kriloff pressure in phase.
- A damping force is then applied.

Consider the same panel, only now rotated 90 degrees, as illustrated in Figure 15. The panel is free to displace in z-direction. The panel is located at a depth of 3 meters.

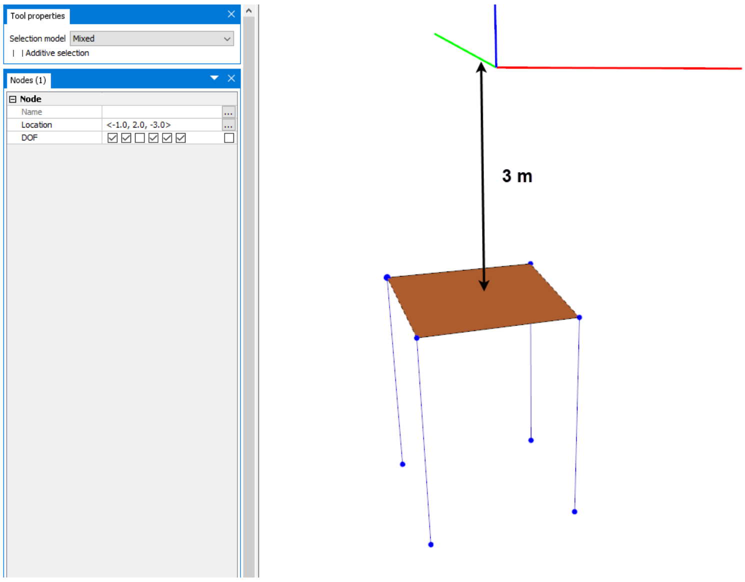

Figure 15 Panel restrained with truss elements

An analysis with the same parameters as presented in Table 2 is run. This will result in forces as shown in Figure 16.

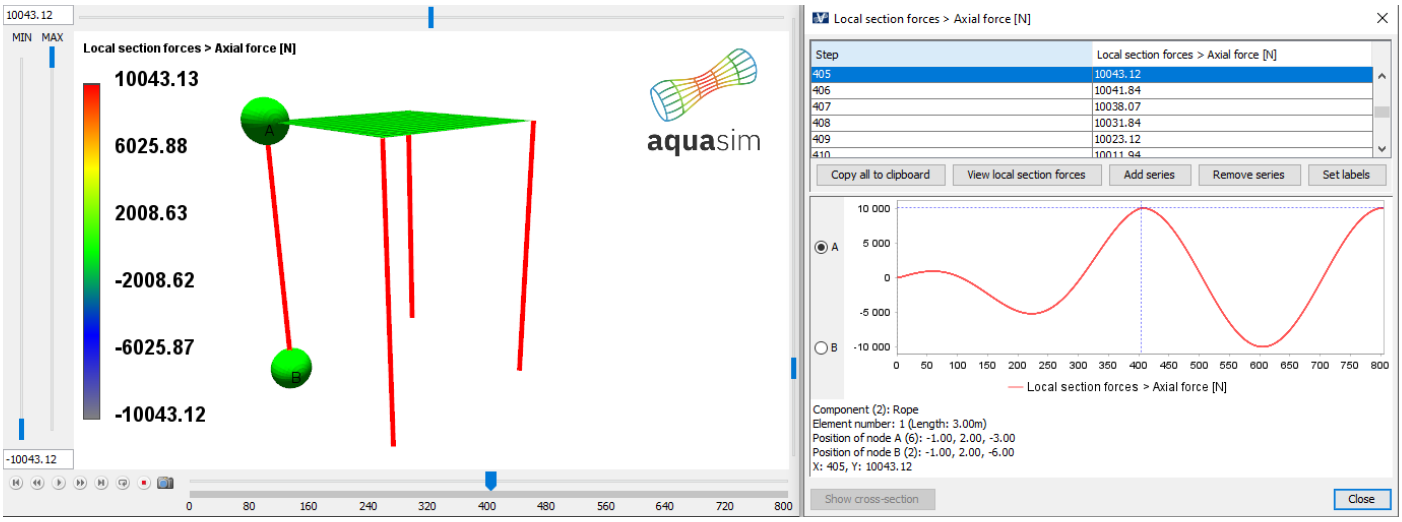

Figure 16 Axial force for panel restrained with truss

Conducting the same analysis, now applying the function Linebreake to observe the vertical motion of the panel. The resulting displacement in z-direction is presented in Figure 17.

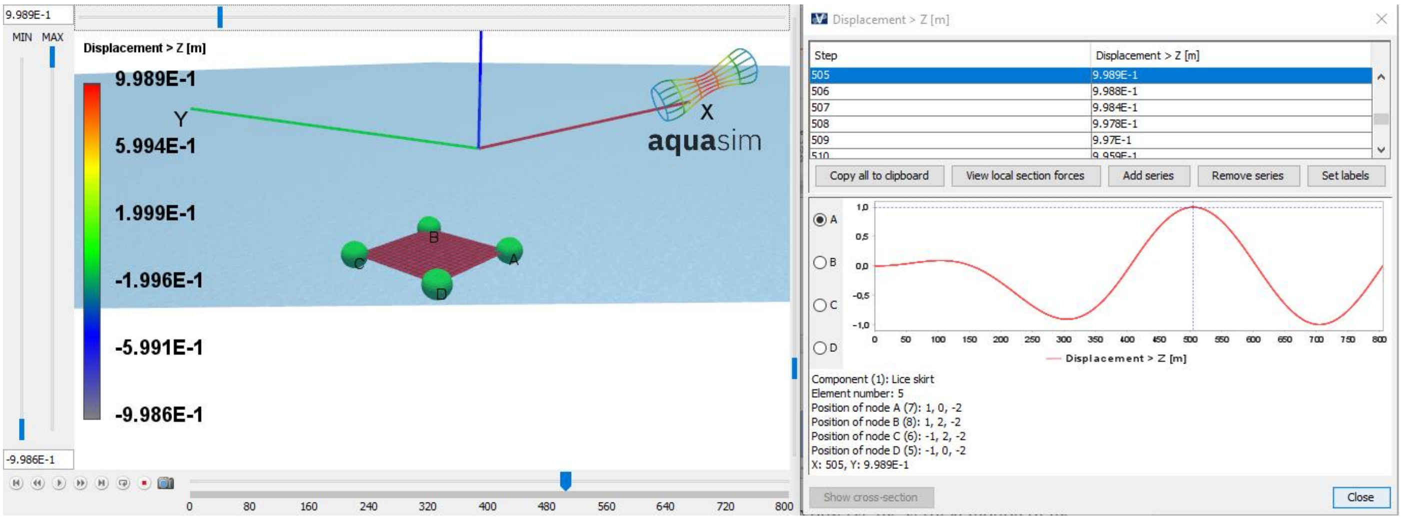

Figure 17 Vertical motion of panel

Figure 18 presents how the Froude-Kriloff dynamic wave pressure is in phase with the vertical displacement in Figure 17.

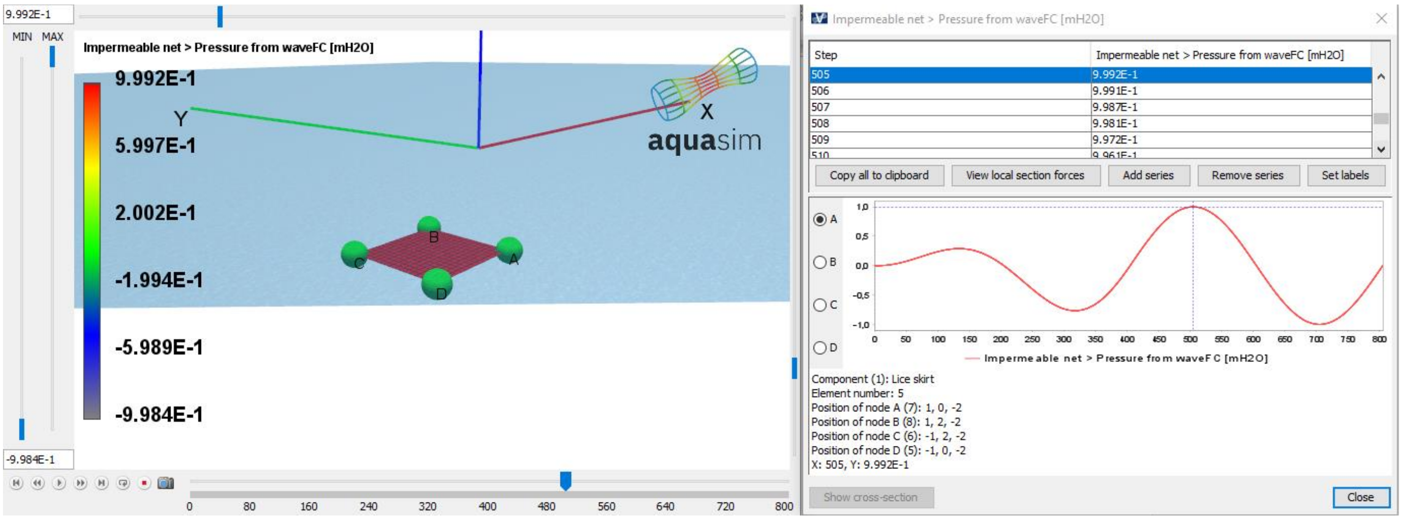

Figure 18 Froude-Kriloff pressure in [mH2O]

By comparing Figure 18 and Figure 16 it is observed that the axial force in the truss is 90 degrees ahead of the wave elevation. This indicates that when the response is governed by damping term, the vertical motion (as shown in Figure 17 and Figure 18) is in phase with the Froude-Kriloff pressure.

4.3 Damping coefficient (flexible tarp) (Bytte figur til ny default tangential)

As lice skirts are highly flexible, their behavior can be characterized as damping-dominated, where the response amplitude is mainly determined by how much the lice skirt resist motion through damping. In AquaSim, the two parameters controlling the response of the lice skirt are shown in Figure 19.

Damping coefficient (flexible tarp) normal	1.0
Damping coefficient (flexible tarp) tangential	0.05

Figure 19 Coefficients controlling the response of lice skirt in AquaSim

These coefficients are implemented to AquaSim as follows:

- **Damping coefficient (flexible tarp) normal:**
  Regulates the damping force in direction normal to the membrane panel as described in Equation 5, and reproduced below:

$$F_{D(normal)} = \frac{Damping\ coefficient(flexible\ tarp) \cdot A\rho g}{\omega}$$

- **Damping coefficient (flexible tarp) tangential:**
  Regulated the damping force in direction tangential to the membrane panel. The same damping as in the normal direction is applied here and scaled with the coefficient. Meaning:

$$F_{D(tangential)} = Damping\ coefficient\ (flexible\ tarp)\ tangential\ to\ panels\ \cdot F_{D(normal)}$$

5 The hybrid load formulation

The hybrid load formulation is applied for calculation of wave excitation loads by combining two load formulations. Two hybrid options are available:

- **Hybrid flexible tarp/ Numerical diffraction:** combines the Flexible tarp method with the Numerical diffraction.
- **Hybrid flexible tarp/ MacCamy-Fuchs:** combines the Flexible tarp method with the MacCamy-Fucs.

Both hybrid methods work with the same principle: the wave excitation loads are calculated as a weighted combination of the two load formulations. The weighting, or scaling, is defined through the factor “Diffraction scaling” in AquaSim. For example, selecting Hybrid flexible tarp/ numerical diffraction with a “Diffraction scaling” factor of 0.25 imply:

- 75% of wave excitation loads are found from the “Flexible tarp” method.
- 25% wave excitation loads are found from the “Numerical diffraction” method.

The same relation is applied for radiation loads (added mass and damping) in AquaEdit. That is, if diffraction scaling is 0.25 then added mass- and hydrodynamic damping coefficients will be 0.25. The damping coefficients (flexible tarp) will be 0.75. This is illustrated in Figure 20.

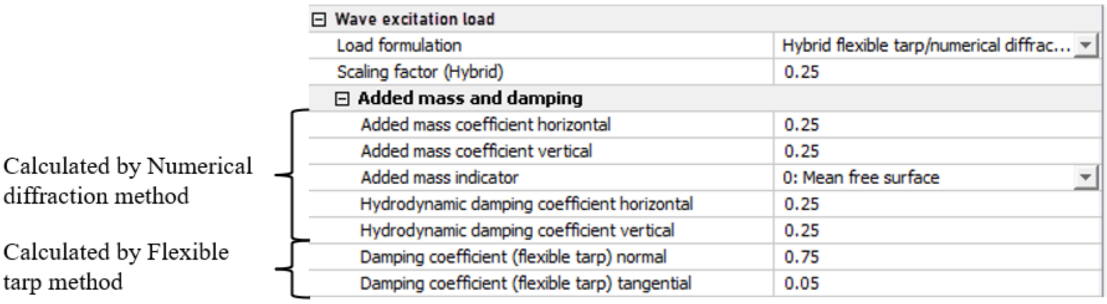

Figure 20 Hybrid model for calculation of wave excitation- and radiation loads

So, when is the hybrid load formulation useful? The hybrid method is useful when having, for example, semi-rigid or moderately deformable structures. As the pure "Flexible tarp" method does not account for diffraction terms, applying this would lead to underprediction of forces. While "Numerical diffraction" also accounts for scattering of waves (i.e. diffraction term), this method alone could overpredict the forces. The hybrid method will then account for damping and hydroelasticity from "Flexible tarp", and at the same time include partial diffraction effects from "Numerical diffraction".

6 Analysis compared with tank testing

To evaluate how well the numerical model represents a lice skirt, a tube has been subject to tank testing, see reference (Aquastructures AS, 2019) and (Roaldsnes, 2020). Forces measured during tank testing were compared with AquaSim analyses applying different sets of parameters. The forces are compared in terms of axial force in bridles, as shown in Figure 21.

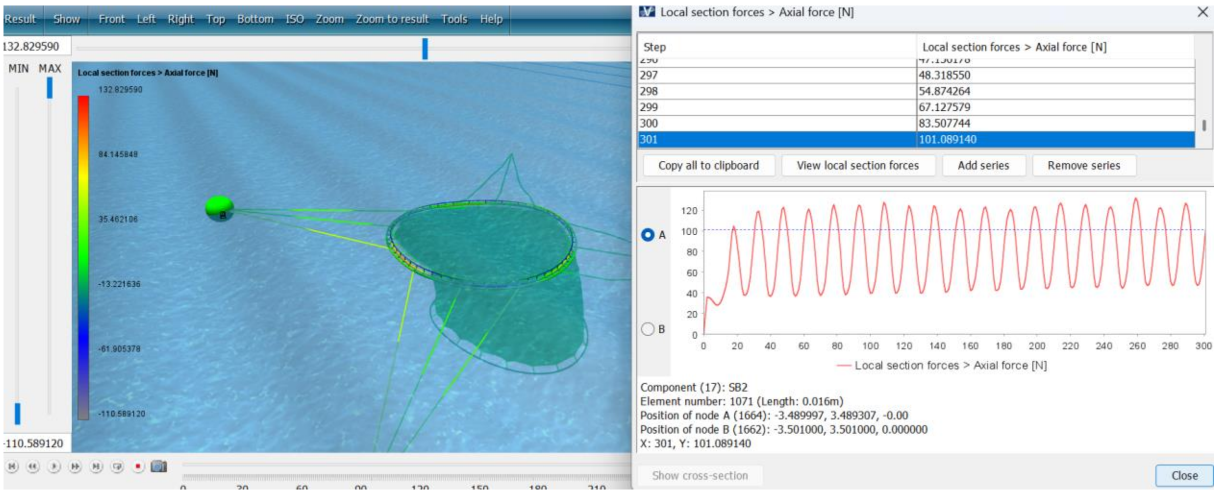

Figure 21 AquaSim analysis of tube. Results show axial force in bridles

Three load cases have been investigated, with different combinations of current velocity and wave amplitude. These are presented in Table 4.

Table 4 Load cases investigated during tank testing

	Case 1	Case 2	Case 3
Current velocity [m/s]	0.097	0.145	0.193
Wave amplitude [m]	0.0988	0.0988	0.0988
Wave period, nominal [s]	1.217	1.244	1.271
Wave period earth fixed [s]	1.158	1.158	1.158

Analyses have been conducted applying the "Hybrid flexible tarp/ Numerical diffraction" load formulation. Input parameters to AquaSim is presented in Table 5.

Table 5 AquaSim input parameters

Analysis cases	**Analysis 1**	**Analysis 2**	**Analysis 3**	**Analysis 4**
Cd front	0.50	0.80	1.00	1.20
Cd back	0.25	0.40	0.50	0.60
Ct	0.00	0.00	0.00	0.00
Cl	0.00	0.00	0.00	0.00
Inner mass	0.00	0.00	0.00	0.00
Load formulation, Hybrid flexible tarp / Numerical diffr.	Yes	Yes	Yes	Yes
Diffraction scaling	0.25	0.25	0.25	0.25
Added mass coefficient horizontal	0.25	0.25	0.25	0.25
Added mass coefficient vertical	0.25	0.25	0.25	0.25
Added mass indicator (2 = conservative, actual water line)	2	2	2	2
Hydrodynamic damping coefficient horizontal	0.25	0.25	0.25	0.25
Hydrodynamic damping coefficient vertical	0.25	0.25	0.25	0.25
Damping coefficient (flexible tarp)	1	1	1	1
Damping coefficient (flexible tarp) tangential to panels	0.05	0.05	0.05	0.05
Include drift	Yes	Yes	Yes	Yes

It should be noted that the parameter Damping coefficient (flexible tarp) was specified to 1.0, although the hybrid model suggests differently. It was found that this provided good agreement with the observed response of the tube. The default values of AquaSim parameters are generally set with conservatism in mind. However, the user must evaluate this case-by-case and make potential adjustments.

6.1 Case 1

The measured test data has been compared with AquaSim analysis with a variation in drag coefficients, as seen in Figure 22.

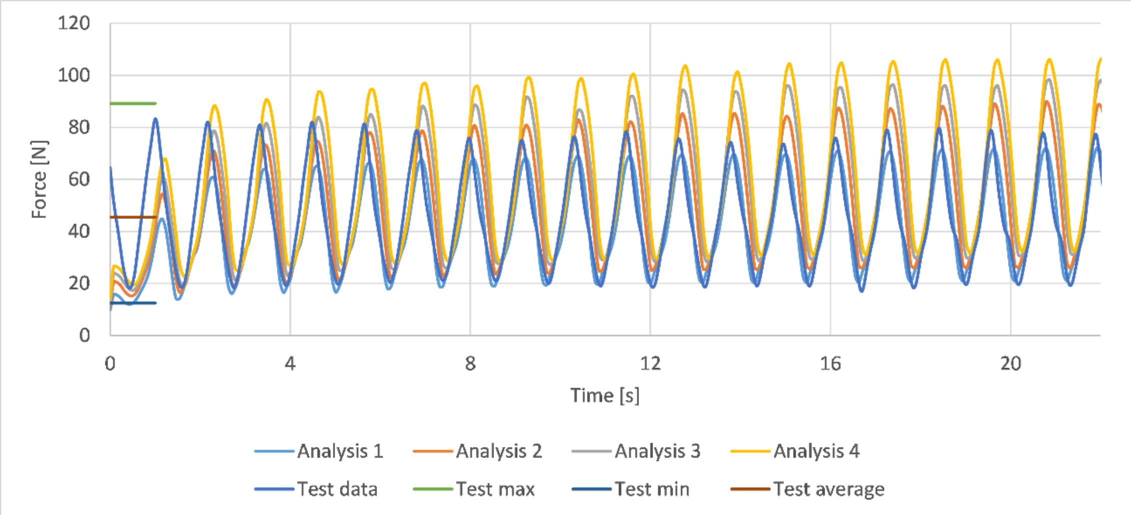

Figure 22 Test data compared with AquaSim analysis for Case 1

The different curves can be explained by:

- **Analysis 1:** AquaSim analysis with parameters as specified in Table 5.
- **Analysis 2:** AquaSim analysis with parameters as specified in Table 5.
- **Analysis 3:** AquaSim analysis with parameters as specified in Table 5.
- **Analysis 4:** AquaSim analysis with parameters as specified in Table 5.
- **Test data:** excerpt of the test data time series.
- **Test max:** observed maximum value from the full test data series (indicated on left side in Figure 22).
- **Test min:** observed minimum value from the full test data series (indicated on left side in Figure 22).
- **Test average:** the average value from the full test data series (indicated on left side in Figure 22).

When we evaluate the results and compare them, the response pattern is similar for all investigated analyses. What is characteristic about the analysis results is that the amplitude of the force increase with increasing drag coefficient. It is noted that the curve "Test data" only is an excerpt from the full time series, whereas the max, min and average are for the full data series.

6.2 Case 2

This case (see Table 4) has an increased current velocity compared with Case 1, whereas the wave amplitude is the same. The results from AquaSim analysis compared with tank test data are shown in Figure 23. Also, in this case it is observed that AquaSim results achieve similar response pattern as the test data. When we consider the amplitude of the load from AquaSim analyses and compare with the max- and min-values from test data we see that they fall reasonably within.

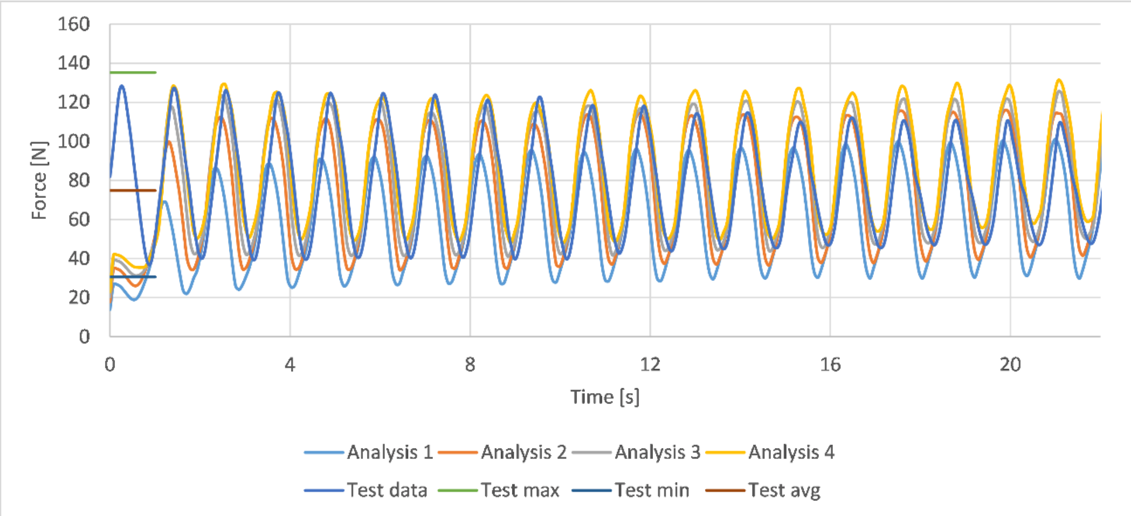

Figure 23 Test data compared with AquaSim analysis for Case 2

6.3 Case 3

This case has also an increased current velocity compared with Case 2, whereas wave amplitude is the same. The results from AquaSim analysis compared with tank test data are shown in Figure 24.

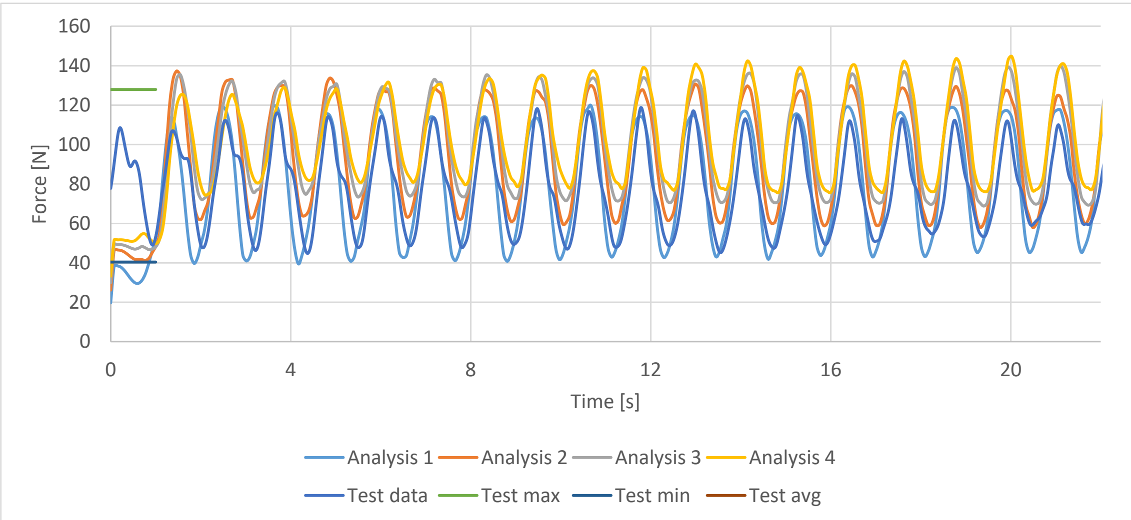

Figure 24 Test data compared with AquaSim analysis for Case 3

Figure 25 presents a photograph from the tank test Case 3, while the corresponding condition from AquaSim analysis is shown in Figure 26. The purpose of this presentation is to highlight selected similarities and differences between physical and numerical models. The upper section of the tube in the experiment appears adhered more to the water surface, both upstream and downstream. Suggesting that more fluid is entrapped along the tube compared with analysis. Although not illustrated here, the numerical model reproduces the response of the bottom ring in good agreement with the experimental observations.

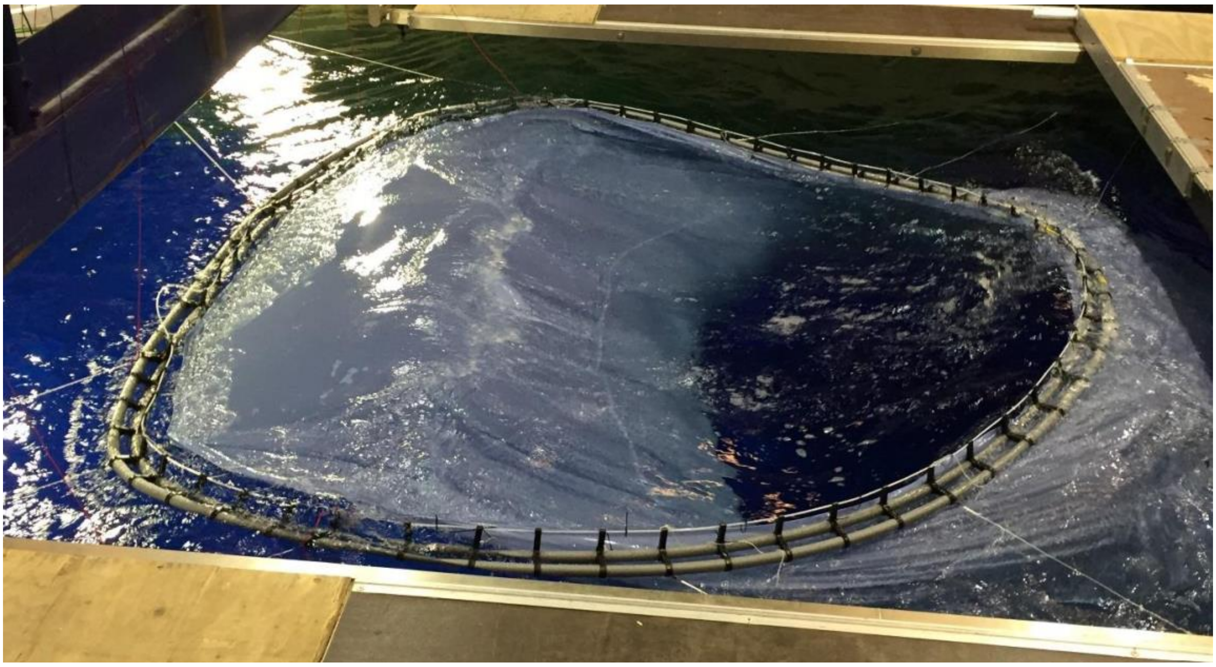

Figure 25 Photo from tank test with tube exposed to waves and current

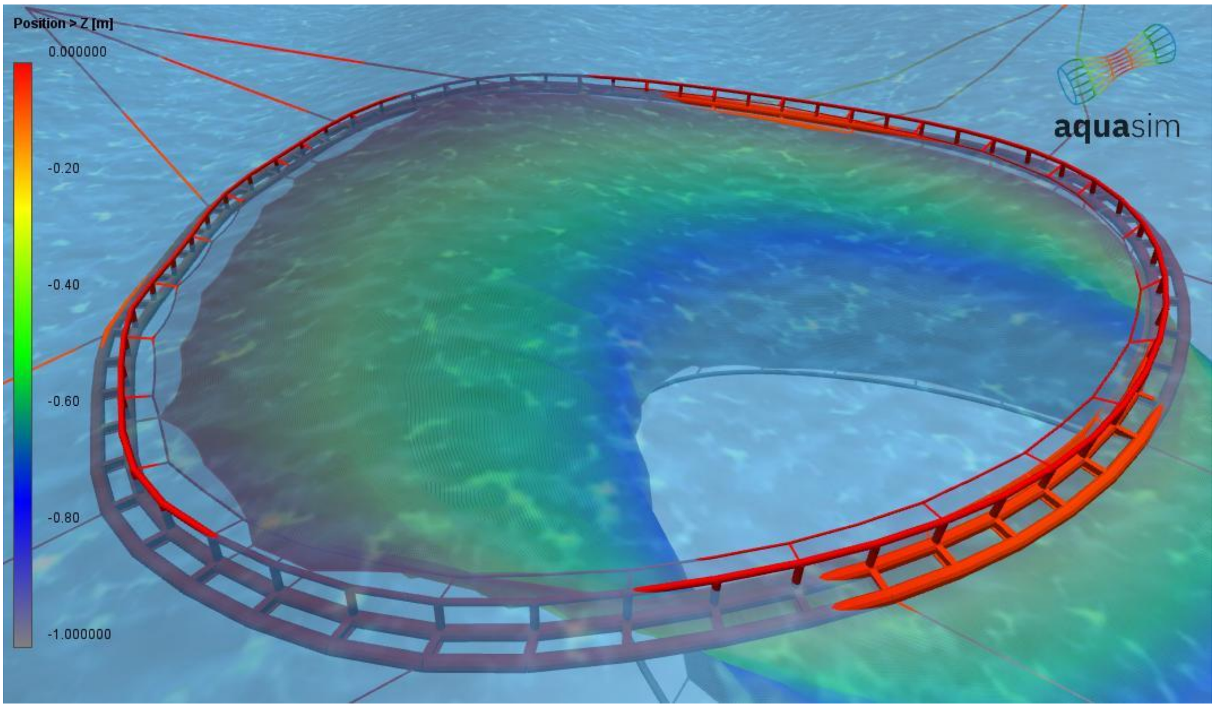

Figure 26 From AquaSim analysis with tube exposed to the same wave and current as in tank test

7 Summary

This tutorial demonstrates how wave induced forces on lice skirts are calculated by AquaSim. The different methods for estimating wave excitation- and restoring forces are presented, followed by simple analysis examples, applying "Flexible tarp" method, is shown to illustrate panel response in both horizontal and vertical direction. In addition, the hybrid method "Hybrid flexible tarp/ Numerical diffraction" is introduced along with some examples of application.

The final section illustrates how wave loads, combined with current, on a tube can be represented in AquaSim applying the hybrid method between Flexible tarp and Numerical diffraction. It is seen that the hybrid method provides realistic load distributions and structural response. However, it should be noted that there will be some uncertainties regarding the selection of coefficient values given limited empirical data at present. Looking ahead, further validations with full-scale measurements and experiments with broader application areas of impermeable and flexible structures will contribute to reduce uncertainties.

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9 Revision comments

Revision no.	**Comment**
1.0	First publication

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