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ANALYSIS OF FLEXIBLE NET STRUCTURES IN MARINE ENVIRONMENT

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Abstract. The classic aquaculture units are flexible net structures where loads from the marine environment are drag-dominated. Such systems are normally analysed using computer intensive dynamic hydro-elastic analysis. The current analysis culture is to apply a regular design wave analysis to cage grids which are drag dominated, while irregular analysis is applied to barge units which are mass dominated. This is mostly due to time efficiency, but has been under the assumption that the drag dominated systems have less need for irregular analysis to obtain a realistic estimate for the max design response value.

This paper does extensive analysis of a classic aquaculture cage case to compare the regular and irregular response analysis. Response from regular wave analysis is compared to response from three hour long time series of irregular waves. Extreme value statistics are derived and results are discussed.

1 INTRODUCTION

The aquaculture industry in Norway has increased rapidly the last decades. In the early years the industry was regulated only under the laws for free enterprise until the first specific laws were put into place in 1973. Since then, rules and regulations have evolved and in 2003 the Norwegian Standard NS 9415 [3] was introduced, establishing design criteria. In 2009 the NS 9415 was revised and in 2011 corresponding regulations were enforced. Structural integrity to defined load criteria had to be documented. This largely increased the engineering effort within the industry and as more systems were assessed and documented to this regime, the number of escaped fishes plummeted. NS 9415 is currently under revision with scope to enhance safety even further.

The classic aquaculture units are drag-dominated structures. About 90% of the fish farms in Norway are based on polyethylene floating collars with a flexible net underneath as shown in Figure 1.

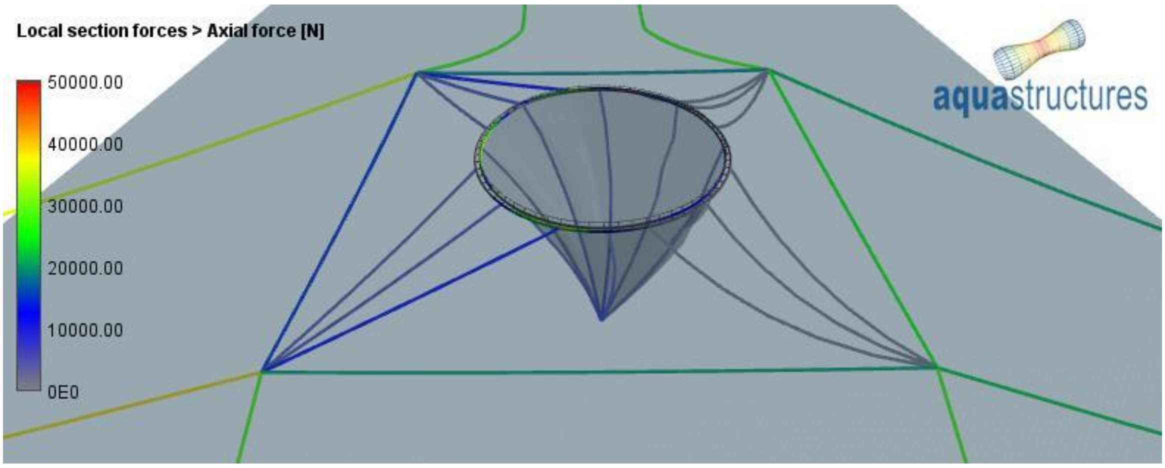

Figure 1 Conically shaped net in floating collar

Figure 1 shows a conically shaped net. The net cages are normally laid out in a grid like the one shown in Figure 2.

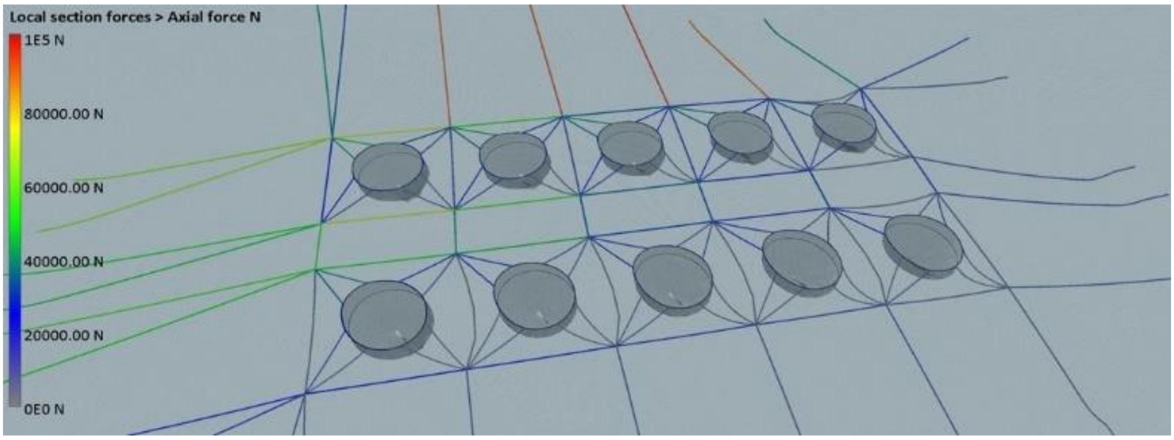

Figure 2 Grid system

2 THEORETICAL BASIS FOR THE AQUASIM ANALYSIS

The analysis presented in this paper are carried out with the FEM software-tool AquaSim. AquaSim is the most commonly used analysis tool for finding response of Aquaculture units from wind, current and waves worldwide. The AquaSim software is based on the finite element method. It utilizes beam and shell elements with rotational degrees of freedom, (DOF's), as well as membrane elements and truss elements with no rotational stiffness. Geometric nonlinearities are accounted for in all element types, such that the program handles large structural deformations. The program is based on time domain simulation where it is iterated to equilibrium at each time instant. Both static and dynamic time domain simulation may be carried out. Features such as buoys, weights, hinges and springs are included in the program.

The basic idea of the FE analysis program is to establish equilibrium between external loads acting on the structure at a given time instant and internal reaction forces:

$$\sum F = R_{ext} + R_{int} = 0 \tag{1}$$

where R_{ext} is the total of the external static forces acting on the structure at a given time instant and R_{int} is the internal forces. The structure is discretized to a finite number of DOF's. Equation 1 is then discretized as:

$$F^{idof} = R_{ext}^{idof} + R_{int}^{idof} = 0, \qquad idof = 1, N_{dof} \tag{2}$$

where N_{dof} is the discrete number of DOF's the structure has been discretized into. The current element program deals with strongly nonlinear behaviour both in loads and structural response. To establish equilibrium, the tangential stiffness method is used. External loads are incremented to find the state of equilibrium. Having established equilibrium in time step ***i-1***, the condition for displacement ***r***, step ***i***, is predicted as:

$$\Delta R^{i}(r_{i-1}) = R_{ext}^{i}(r_{i-1}) + R_{int}^{i-1}(r_{i-1}) = K_t^{i-1}\Delta r \tag{3}$$

where $\boldsymbol{K_t^{i-1}}$ is the tangential stiffness matrix at configuration ***i-1***. The external load is calculated based on the configuration of the structure at ***i-1***. This gives a prediction for a new set of displacements ***(j=1)***. Based on Equation 3, a prediction for the total displacement $\boldsymbol{r_{(j=1)}}$, is found as:

$$\bar{r}_{j-i} = r_{i-1} + \Delta r \tag{4}$$

Based on this estimate for new displacements, both external and internal forces are derived based on the new structural geometry and the residual force, $\boldsymbol{\Delta R}$ is put into the equation of equilibrium as follows:

$$\Delta R(\bar{r}_i) = R_{ext}^{i}(\bar{r}_i) + R_{int}^{i}(\bar{r}_i) = K_t^{i}\Delta r \tag{5}$$

Note that both the external and internal forces will vary for each iteration due to the strongly hydro-elastic nature of the fluid structure interaction. Equation 5 is solved for the displacement $\boldsymbol{\Delta r}$. Incrementing ***j*** with one, the total displacement is now updated as:

$$\bar{r}_j = \bar{r}_{j-1} + \Delta r \tag{6}$$

Now if Δr found from Equation 5 is larger than the tolerated error in the displacements, Equation 4 is updated ***(j = j+1)*** and Equation 5 is solved based on the new prediction for displacements, this is repeated until, $\boldsymbol{\Delta r}$ is smaller than a tolerated error, then:

$$r_i = \bar{r}_j \tag{7}$$

i is increased with one, and Equation 4 is carried out for the new load increment.

At the default configuration, the software works as this: Static analysis is used to establish static equilibrium including buoyancy. Secondly, current loads are applied then wind and wave loads are added (still static analysis). Then dynamic analysis commences. Waves are introduced with the first wave used to build up the wave amplitude. Both regular waves and irregular waves may be simulated. Waves are assumed to be sufficiently described by linear wave theory. Inertia and damping are accounted for in the wave analysis, meaning that mass and damping are accounted for in the equations of equilibrium. The Newmark-Beta scheme is applied for the dynamic time domain simulation. Note that the above equations imply using the Euler angles for rotations. This is just a simplification for easy typing. For rotational DOF´s AquaSim uses a tensor formulation for the rotations as outlined in e.g. [10] which should be applied to handle 3D rotations in an appropriate manner.

Wave loads may be derived using the Morison formulae [6] or using diffraction theory [9]. For elements where the Morison formulae is applicable the cross-flow principle is applied for beams and truss elements [9]. The drag load term of this equation is quadratic with respect to the relative velocity between the undisturbed fluid and the structure. Both the mass of the structure as well as added mass in the cross-sectional plane is accounted for. Due to the large deflections occurring, the added mass is nonlinear. For permeable nets the method presented in [11] is applied. A main difference in the drag load on permeable net compared with drag loads to truss is the increase of the drag due to the presence of the permeable net. [11] formulated this as an increased drag coefficient:

$$Cd_{mem} = Cd_{cyl} \frac{1}{\left(1 - \frac{Sn}{2}\right)^3} \tag{8}$$

where Sn is the solidity of the net.

A further description of load and response for permeable nets in AquaSim is described in [4] and [11].

AquaSim has been used commercially for more than 15 years and has throughout the years undertaken a versatile verification scheme: Analysis has been carried out on a wide range of computational cases where results have been compared to handbook formula or other programs [4]. As early as in 2004 model experiments were carried out and compared to analysis [5]. AquaSim has been compared to accidents where the capsize origins were known [1], [2]. In addition, experience have been obtained during several years where AquaSim has been the most used software for calculation of the structural integrity of fish farm systems in Norway, as well as in other regions with similar aquaculture systems including Chile, North America and Australia. The cage-system as seen in Figure 2 in general consist of mooring lines, floating collars and nets responding to wave and current in a strongly nonlinear (hydro-elastic) manner. AquaSim is also used for a wide range of offshore applications such as towing for seismic operations [8], operations and installations offshore, mooring analysis of offshore units and structural and mooring analysis of equipment for renewable equipment offshore [7].

3 CASE STUDY: POLYETHYLENE CAGE GRID SYSTEM

The system seen in Figure 1 is used as case study. The system is a 50 meter diameter circular collar with a conically shaped net and mooring as shown in Figure 3 and Figure 4. Details regarding the input-data is given in Appendix.

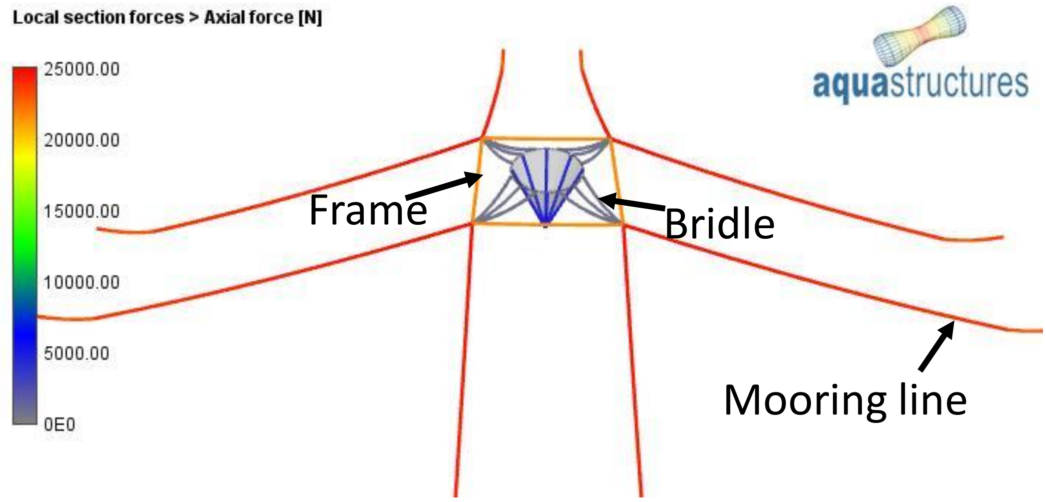

Figure 3 Case study 1, classic polyethylene-based fish farm. Colours represent axial force in still water which is the pretension force. The x- axis points to the right in the figure and the z- axis point upward in ant orthonormal coordinate system.

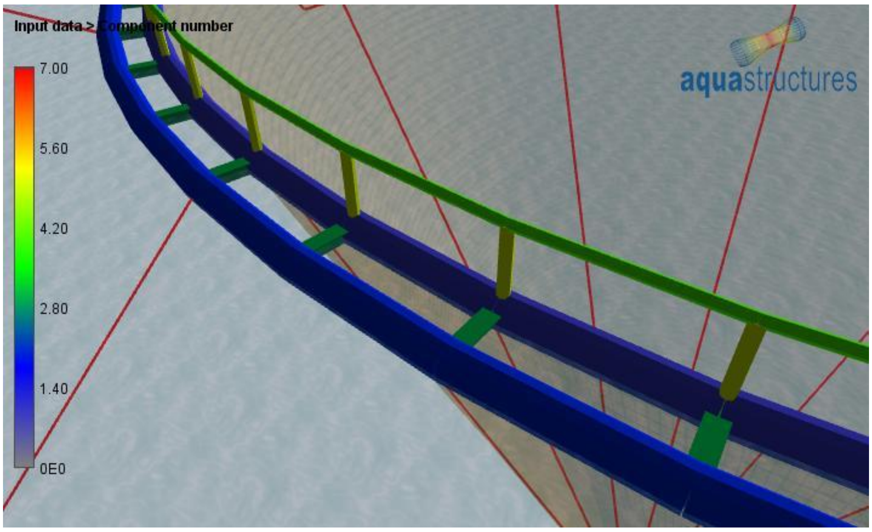

Figure 4 Polyethylene collar. Components are indicated by colour. Component data are given in Appendix.

The most important load component to such system is the drag term of the Morison equation:

$$F = Cd\frac{\rho}{2}dLv^2 \quad (9)$$

Cd is the drag coefficient, d is the diameter of twine or rope and L is the length. The velocity v is the relative velocity between the twine / rope and the flow in the cross-flow direction. Differentiating between velocity cause by waves (v_w), by current (v_c) and by the system (v_s), the combined velocity in the cross-flow direction can be expressed as:

$$v = v_w + v_c - v_s \quad (10)$$

The force acting on the net is squared relative to the sum of the combined cross-flow relative velocity. Hence effects cannot be superposed. The forces depend on both angle of the twine and the effective solidity in the given position. This means that time domain simulations with all effects combined are a necessity.

In AquaSim the current velocity flow is incremented, and static equilibrium is established. Then waves are incremented over one wave period to its full amplitude for regular waves and over a time period = Tz for irregular waves. Figure 5 shows results in terms of axial forces in mooring components for a load case with the environmental data given in Table 1.

Table 1 Environmental data

Parameter	Abbreviation	Value
Current velocity	Vc	0.5 m/s
Current direction	Along x- axis	0.0 deg
Wave type	-	Regular
Wave amplitude	-	2.0 m
Wave direction	Along x- axis	0.0 deg
Wind	Not included	-

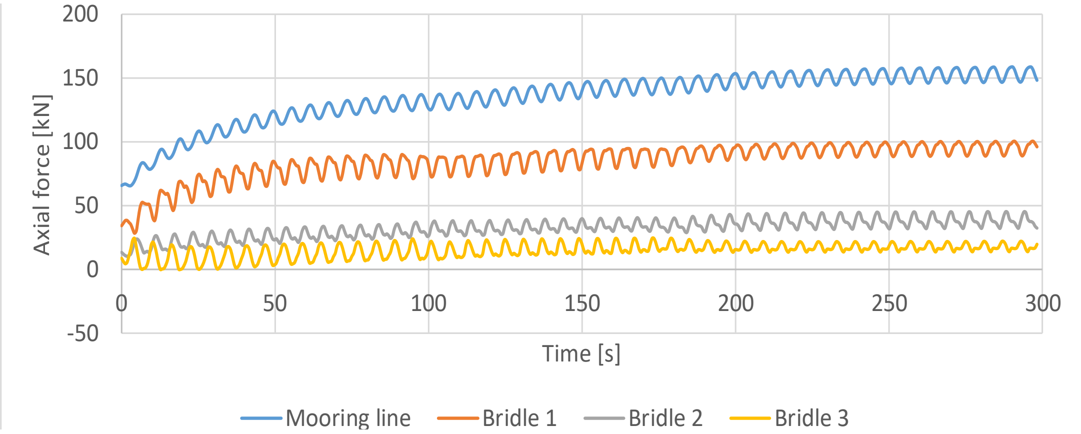

Figure 5 Axial force in 4 lines in the mooring system as function of time. The 4 lines are marked in Figure 6.

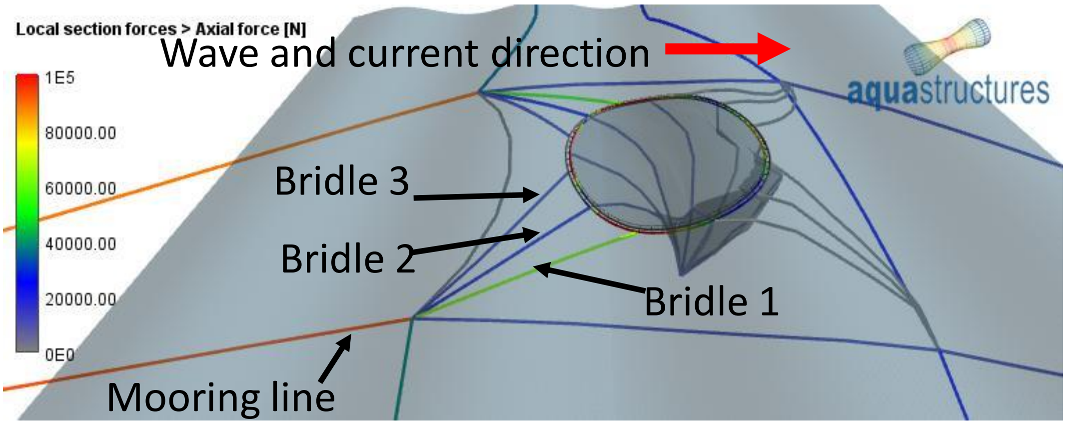

Figure 6 One time instant in the analysis, system is deformed.

As seen from Figure 5 it takes approximately 250 seconds for the response to reach a steady state where the drift-force is fully developed. The fully developed situation for several design waves will of course not occur for the real-life cases. The relation between the response of the n^{th} wave of the regular wave response and peak response in irregular seas is compared.

Figure 7 shows displacement as function of time for the mooring lines.

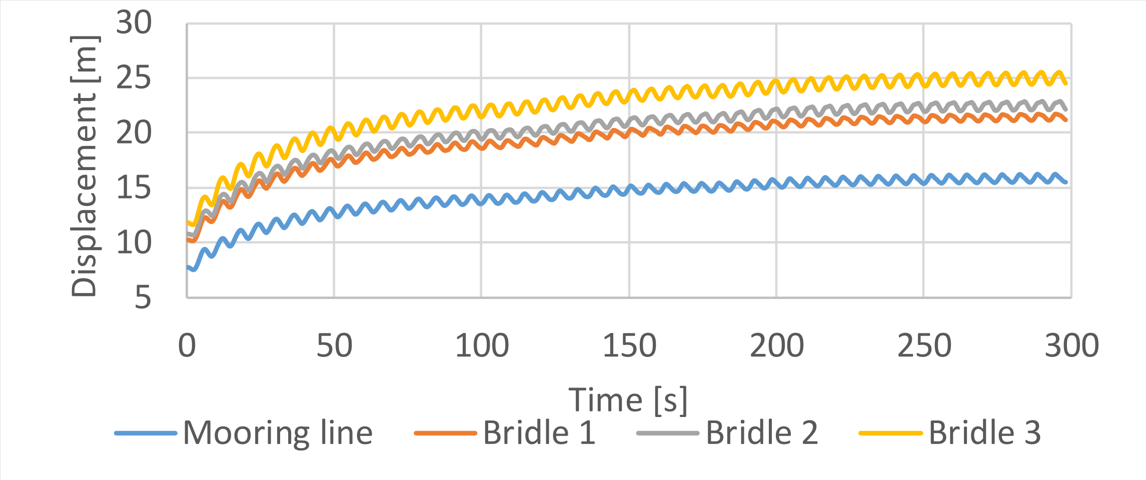

Figure 7 Displacement. Response time series for displacement in mooring lines.

As seen from Figure 7, and comparing to Equation 10 it is seen that the system is pushed in the wave and current direction wave cycle by wave cycle. Since there is an average force in the direction of the wave propagation, the system slides in the wave propagation direction until equilibrium is established, which in this case takes approximately 250 seconds.

Figure 8 presents results for regular waves with amplitude 1.0 meter and a period of 3.0 seconds

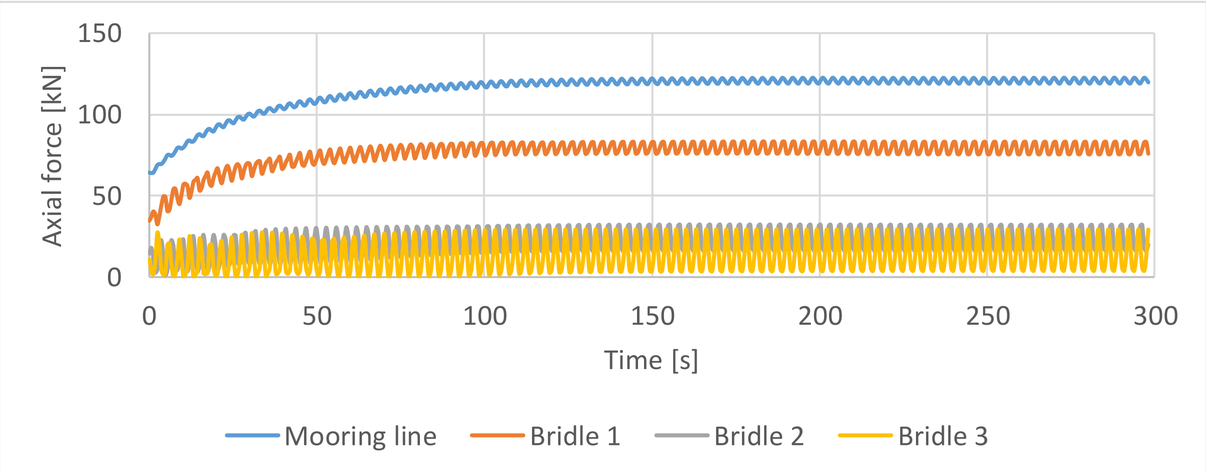

Figure 8 Axial force. Results for regular waves with amplitude 1.0 meter and a period of 3.0 seconds.

Figure 9 shows results for regular waves with amplitude of 3.0 meter and a period of 9.0 seconds

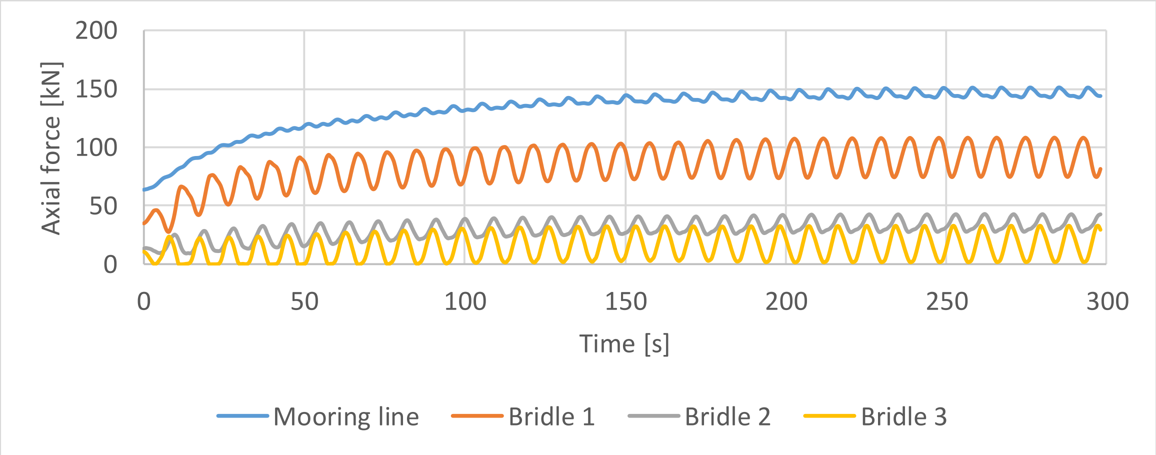

Figure 9 Axial force. Results for regular waves with amplitude of 3.0 meter and a period of 9.0 seconds.

The results presented in Figure 8 and Figure 9 shows the same trend as the results in Figure 5 but note that the wave induced forces in the bridles vary much more for the cases presented in Figure 8 and Figure 9. This illustrates the need for dynamic analysis and it indicates that the closer the mooring component is to the cage (i.e. bridles) the more important the dynamic wave response is. Note that the dynamics relatively is highest for the low loaded bridles. For a design case there are other wave and current directions such that the results seen for Bridle 3 in this paper will not be the dimensioning forces. Hence it is the Mooring line and Bridle 1 that has been chosen for evaluation of results from irregular analysis.

NS 9415 states that the wave in a design wave approach shall be 1.9 times the significant wave height of an irregular wave (i.e. $H_{max} = 1.9 \times H_s$). This paper also analyses this system with irregular waves. The irregular wave parameters are given in Table 2.

Table 2 Key data for analysis in irregular waves

Parameter	Abbreviation	Value
Current velocity	Vc	0.5 m/s
Current direction	Along x- axis	0.0 deg
Wave type		Irregular
Spectrum		Jonswap
Significant wave height	Hs	2.1 m
Peak wave periode	Tp	6.0 s
Peak factor of spectrum		3.1
Wave direction	Along x- axis	0.0 deg
Wind	Not included	-

Figure 10 shows examples of response from 20 minutes of irregular waves. 10 time series have been generated based on different seed for random phases of the wave components with at time length of 3 hours, whereas the figure shows 20 minutes.

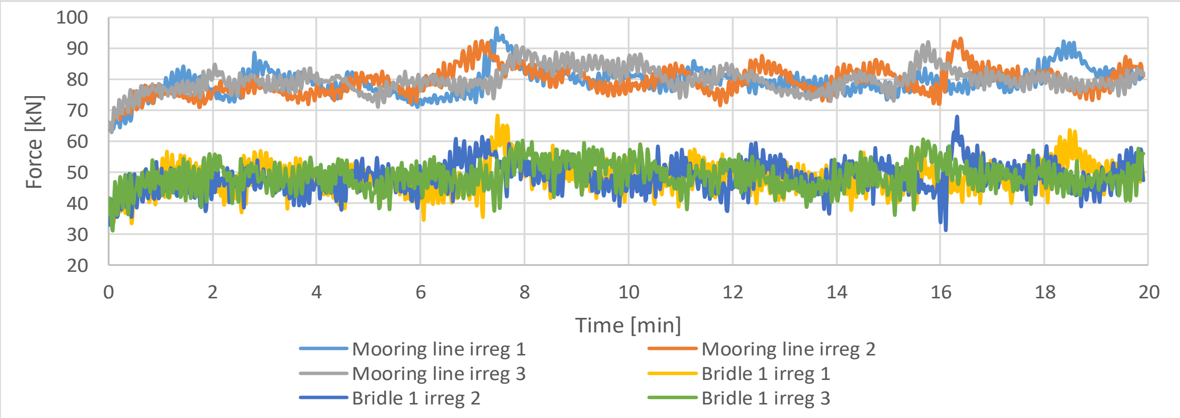

Figure 10 Resulting tensile force in Mooring line and Bridle 1 for three sets of irregular waves.

Discussing the results seen in Figure 10 it is useful to consider the slow drift eigen periods. The eigen periods for the three drifting mode sway, surge and yaw are shown as a function of current velocity in Figure 11.

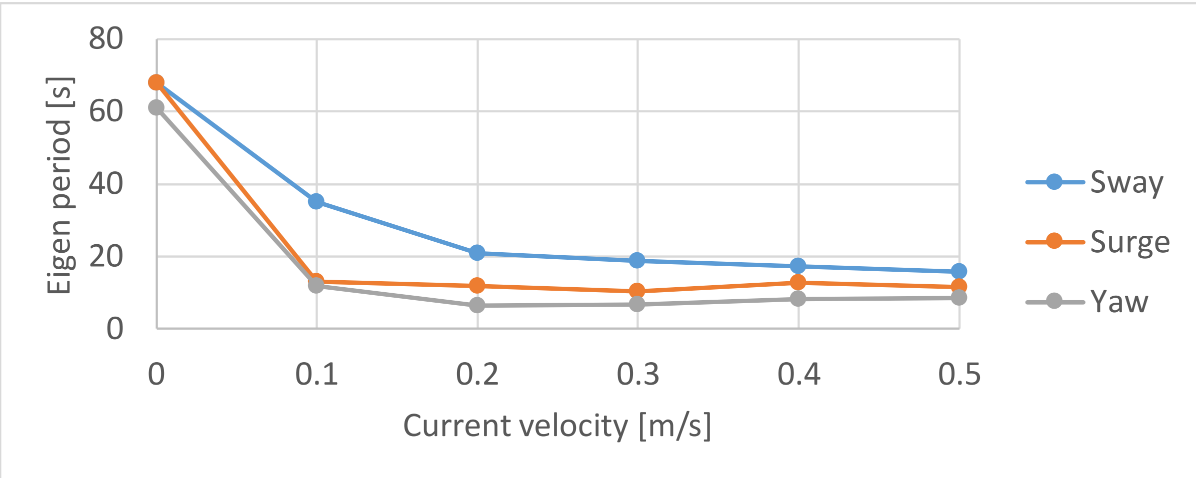

Figure 11 Eigen period for three motions of system as function of current velocity. Surge is transverse to the flow direction.

As seen from Figure 11, the eigen periods of the previously named response modes decrease with increasing current velocity. This is due to that stiffness of the mooring system increase with increasing current velocity. Hence such system will not see frequency domain resonant slow drift behaviour, but rather response better described by an impulse response consideration [12].

The forth eigen period of this system is not roll, heave or pitch, as are the classic eigen periods for stiff systems, but rather the shape seen in Figure 12.

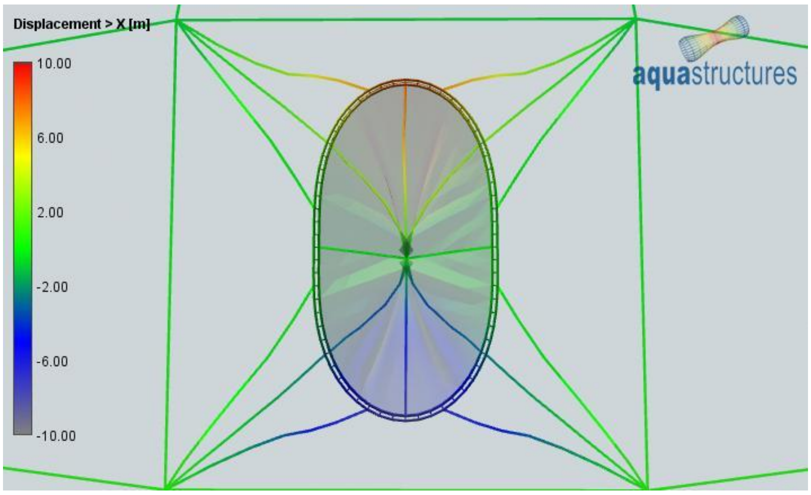

Figure 12 Eigen period at 4.66 seconds (current velocity 0.0 m/s).

As seen from Figure 12 the fourth largest eigen period in this case is an ovalisation of the floating collar. Though the eigen period for this case is in the area of high wave energy. The damping due to drag forces in the net is so high that resonant motions, for classic net pen system, in this shape has not been observed. However, the eigen-shape seen in Figure 12 is an indication to why floating collars may get damage when being stored at sea without nets in them. In such case they do not benefit from the drag damping caused by the net.

Figure 13 presents max force in Mooring line and Bridle 1 from the irregular wave analysis, with 10 different random phases, compared to the max force found from 1 fully developed wave, 2 fully developed waves, 3 fully developed waves and the equilibrium state shown in Figure 5 and Figure 6 (after 250 seconds).

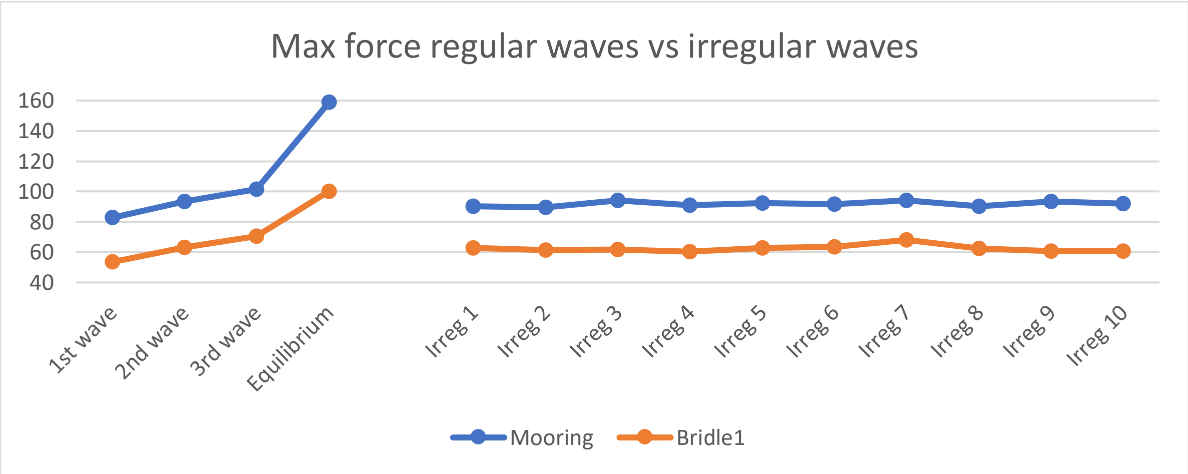

Figure 13 Max force in Mooring line and Bridle 1. Regular and irregular waves.

As seen from Figure 13 the loads from the regular sea analysis are larger after the 3rd wave than for all irregular wave analysis. Whereas the 2nd wave response fall in the range of the irregular sea states and the 1st wave response is lower. Table 3 show the results from the regular wave analysis compared to statistics of the irregular wave analysis. As seen from the table, there is a good correspondence between the 2nd fully developed wave and the irregular wave analysis, which also is seen in Figure 13.

Table 3 Results regular wave analysis compared to statistics of irregular analysis. For the irregular analysis 3 hour sea state has been analysed.

Component	1st wave	2nd wave	3rd wave	Fully developed	Irregular average	Irregular 90 %
Mooring	82.7 N	93.5 N	101.5 N	158.8 N	91.8 N	94.0 N
Bridle 1	53.5 N	63.2 N	70.5 N	100.2 N	62.4 N	63.9 N

This means that the analysis indicates that when estimating maximum response from regular waves, one should at least simulate two fully developed regular waves.

Comparing the results in general it is seen that the current velocity itself make up for a large component of the forces introduced in the system. This means that the risk introduced by regular wave analysis overall is lower than for systems where waves are the largest load component. This will be the case for most classical fish farm systems.

The standard deviation for the irregular wave results are 1.6 % and 3.3 % of the mean values for the mooring and bridle, respectively.

4 CONCLUSIONS

From the analysis carried out one can conclude that one should at least analyse two fully developed regular waves to be in the same range as the irregular waves. Irregular wave analysis is preferable also for such systems, as it reflects better the actual sea state. The drag- and damping effects plays an important role, such that the spread in results are not high and regular waves would be sufficient for the case analysed in this study.

Slow drift eigen periods for fish farm systems are strongly nonlinear and one should consider whether impulse response could be of importance, but for this case the damping was so large that no response to eigen periods were seen. This will be the case for the classical net pen systems with large damping. In case nets are removed or changed to impermeable nets one should investigate if response caused by eigen periods will be of importance.

In further studies, similar analysis should be carried out for a mass dominated system, such as feeding barges and systems with impermeable nets (e.g. lice skirts) or other structures leading to closed water (and hence mass) compartments and relatively lesser damping.

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APPENDIX

This appendix contains model descriptions of the floating collar system used as case study.

Table 4 Properties belonging to the floating collar, beam elements.

Parameter	Inner collar	Outer Collar	Brackets	Handrail	Pole
E-modulus [N/m2]	9.00E+08	9.00E+08	8.00E+08	8.00E+08	8.00E+08
G-modulus [N/m2]	3.46E+08	3.46E+08	3.08E+08	3.08E+08	3.08E+08
Area [m2]	4.43E-02	4.43E-02	1.53E-02	3.74E-03	4.75E-03
Iy [m4]	1.23E-03	1.23E-03	3.15E-04	9.05E-06	1.48E-05
Iz [m4]	1.23E-03	1.23E-03	6.01E-05	9.05E-06	1.48E-05
It [m4]	2.46E-03	2.46E-03	6.79E-05	1.79E-05	2.92E-05
Volume [m3/m]	1.96E-01	1.96E-01	-	-	-
Mass density [kg/m3]	9.53E+02	9.53E+02	9.56E+02	9.59E+02	9.50E+02
Weight in air [kg/m]	4.22E+01	4.22E+01	1.46E+01	3.55E+00	4.06E+00

Table 5 Properties of truss elements

Parameter	Type	Dia. [m]	E-modulus [N/m2]	Length [m]	Depth [m]
Vertical net rope	Rope	14	2.00E+09	60.4	-
Grid	Rope	48	1.80E+09	100x100	6
Bridle	Rope	48	1.80E+09	45 - 50	-
Anchor lines	Rope	52	1.80E+09	320	106
Anchor chain	Chain	32	8.00E+10	50	106

Table 6 Properties for membrane elements.

Type	Dia. Twine [mm]	1/2 mesh width [mm]	E-modul [N/m2]	Solidity incl. fouling [%]
Nylon	2.0	25.0	1.00E+09	24.0