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EXPERIENCE FROM INTRODUCTION OF THE DESIGN CODE NS 9415 TO THE AQUACULTURE INDUSTRY IN NORWAY AND EXPANDING THE SCOPE TO COVER ALSO OPERATIONS

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ABSTRACT

This paper presents the current state of regulations, guidelines and the engineering in the Norwegian aquaculture industry. The statistics of fish escapes is evaluated and the need for further developments of the regulations, in planned revisions, of the Norwegian standard, are laid. Simplified case studies are shown to present the main forces acting on fish farms.

Figure 1 Typical Norwegian fish farm, Loppa, Finnmark (web 2013). Polyethylene cages organized in a mooring grid where the observed buoys marks the corners of the mooring grid located below at 5-10 meters depth.

NOMENCLATURE

A : Cross sectional area, shadow casting area
Cd : Drag coefficient
E: Elastic (Young's) modulus
F: Force
Hs : Significant wave height
L : Length
a : Amplitude impulse response
d : Diameter
k : Stiffness structural system
m : Mass (structural and added mass)
t : Time
v : Velocity
y,z : Directions in y-z plane.
Λ : Constant for knotted nets
η :Wave amplitude
ω : Wave frequency
ρ :Fluid density
ζ : Wave elevation

mem : Membrane
cyl : Cylinder

INTRODUCTION

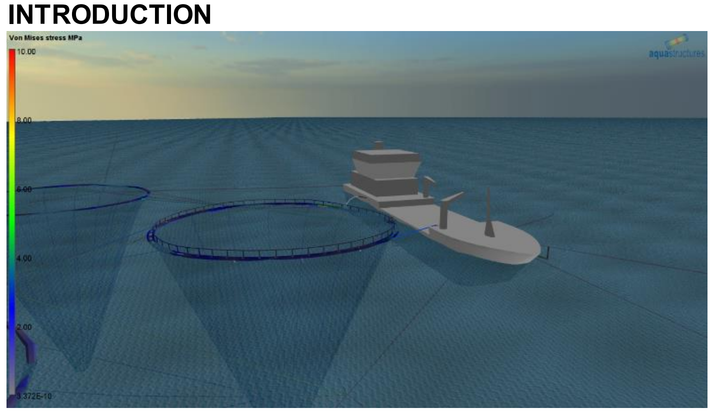

Figure 2 Fish farm operation. AquaSim analysis model. Typical fish farm outline. Conically shaped nets in polyethylene floating collars.

The aquaculture industry has increased rapidly the last 30 years. In 2003 the Norwegian standard NS 9415 was introduced, establishing design criteria that all fish farms must comply with, in order to be acknowledged for use in Norway. Structural integrity to defined load criteria had to be documented. This largely increased the engineering effort within the industry and as more and more systems were assessed to this regime, the number of escaped fish plummeted (see Figure 3). In 2009, the Norwegian standard, NS 9415 was revised and in 2011 corresponding regulations were enforced.

Today salmon production has increased to a level almost three times higher than that of 2003. Fish farm facilities have grown larger and vessel operations, such as well boat operations and operations for delousing fish, are carried out with much larger vessels than in 2003. Now more incidents of fish escapes happen during operations than in storm weather (Figure 10).

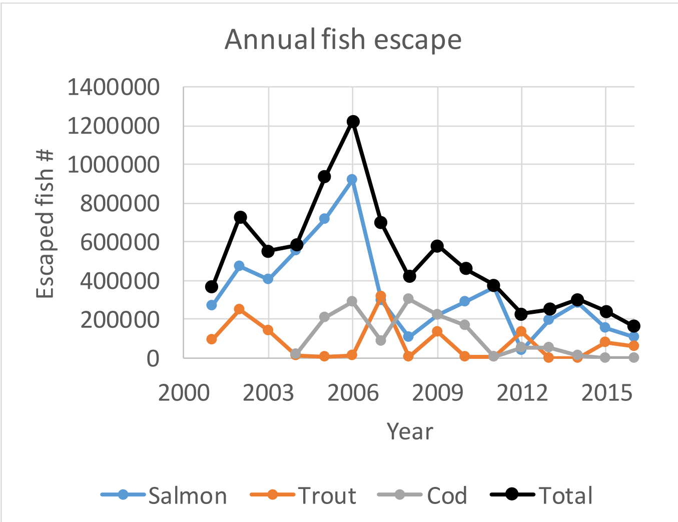

Figure 3 Annual fish escape from Norwegian Aquaculture facilities (fdir 2016)

The Aquaculture industry in Norway is governed by NYTEK regulations, for technical standard of floating aquaculture units (FDIR – 2009), and the Norwegian standard NS 9415 (Figure 5), Marine fish farms - Requirements for design, dimensioning, production, installation and operation.

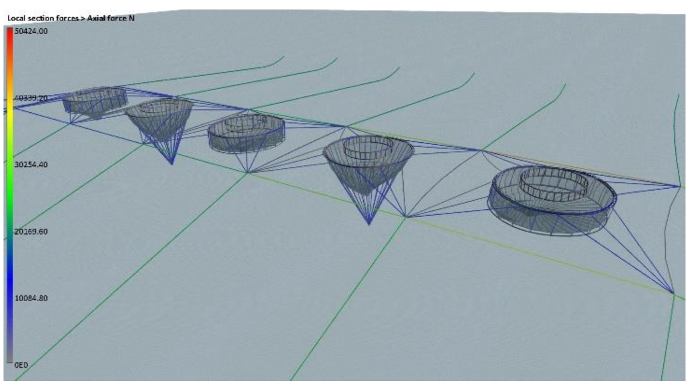

Figure 4 Typical polyethylene based system. All polyethylene collars with either wall sided net shape, or a variation of a conical net shape called the "spaghetti" shaped net. The collars are organized in a single row grid mooring system. 3 bridles attach the floating collars to each corner of the mooring grid.

The standard covers the full cycle of floating fish farm units, i.e. risk assessment, environmental loads and load applications through limit state design. Capacity and system integrity need to be documented. The standard also sets requirements for user manuals to be standardized and consistent with designs.

NS 9415 is an open standard, designed not to prevent innovation. However, the detail level is largest for the most commonly existing aquaculture units as today. This is illustrated by the fact that the criteria for the net pens, floaters and mooring lines are elaborated in the standard. This means that it is easier to apply the standard for classically shaped units such as polyethylene based system (Figure 4), and steel cage system (Figure 6). It is in line with other standards that the typical cases are covered more in detail.

DESIGN CODE NS 9415

To date the design code NS 9415 is the only standard for fish farm systems worldwide. The full name of NS 9415 is "Marine fish farms - Requirements for design, dimensioning, production, installation and operation".

The definition of a standard is (Regjeringen.no 2006): "A standard is a voluntary contract document that describes a product, service and/or work process. The purpose of standardization is to ensure uniformity, order and simplification, and to contribute to efficient operations and increase profitability. Standards provide equal competition terms and make the rules of the game known."

Figure 5 NS 9415, front page.

As seen from the title of NS 9415, the scope is not limited to design and dimensioning, but also production, installation and operation.

The Standard is organized with the following sections:

- Site surveys

- Load and load combination
- General requirements regarding main components and marine fish farms
- Requirements regarding net pens
- Requirements regarding the floating collar
- Requirements regarding rafts
- Requirements for mooring
- Annexes

As seen from the list it starts out with a site survey followed by a load and load combinations. Then follows the capacity assessment. First general requirements, then specific requirements for components that are typically used in the design of fish farms today (like seen in Figure 4 and Figure 6). The general requirements covers more than capacity checks. Requirements are set out also for e.g.:

- Tests
- Delivery
- Inspection
- Operation
- Product specification
- User handbook

Note in particular the section "User handbook". NS 9415 have very strong requirements for user handbooks. The user handbook shall comply with the specified criteria in the following sections:

- General
- Producer and product identification
- Main component and constituent parts
- Transport and storage
- Assembly
- Interfaces to other components
- Operation
- Maintenance
- Log

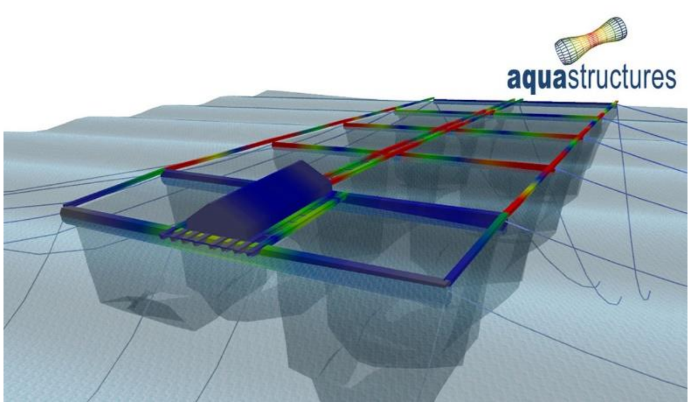

Figure 6 Typical steel cage system, "catamaran" type. Bridges in longitudinal direction are welded to pontoons in the transverse direction. This unit consist of one 8 shaped section with food storage, then 4 E section hinged to one another.

This means that the outline and content of user handbooks have become rather standardized for aquaculture facilities, meaning the overall safety increases since all parts operating have a common understanding of where to find relevant information.

THE NYTEK REGULATIONS FOR THE FISH FARMING INDUSTRY

The NYTEK regulations (Regjeringen 2006) was originally put forward in 2003 and then revised in 2011 (Lovdata 2011) which is the newest revision. The NYTEK regulations refers to the design code NS 9415 for technical criteria. This means the it is NYTEK that is the law any party operating in the Norwegian fish farming industry needs to comply with. However, what is required in NYTEK says that a fish farm shall comply with the technical criteria in NS 9415 or equivalent such that it plausible to revise the two in "tandem". The NYTEK regulation is hence planned for revision 2017 along with the planned revision of NS 9415.

As shown in Figure 7 NYTEK is based on an accreditation / certification regime. All floating fish farm units in Norway need to have the following accredited documents:

- Site survey report
- Mooring analysis report
- System certificate

All which are documents that must be issued from accredited bodies. This is to ensure that equipment is dimensioned to withstand the environmental forces at the given site.

All companies producing main components (i.e. net pens, floating collars, mooring lines, barges etc.) to fish farms need to have a "Producers certificate", and products need to have a "Product certificate". This is to ensure that equipment can sustain the environment they claim to sustain.

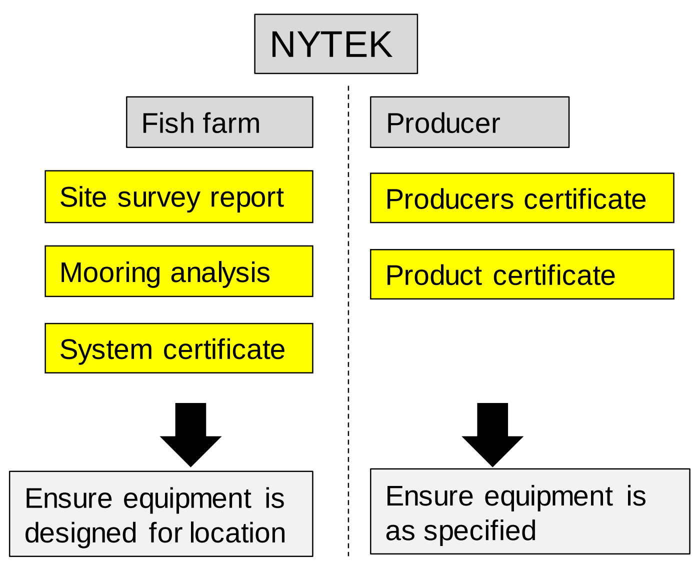

Figure 7 The system of the NYTEK regulations. Yellow boxes are accredited documents

As seen from Figure 7 the current NYTEK requires an accredited mooring analysis whereas there are no such requirements for net pen analysis or analysis of a complete system. As of today, the combined response of a complete system is assumed satisfactory covered in a mooring analysis, where nets and collars are modelled in a less refined way than in more detailed analysis of such parts. Forces interacting between mooring lines and floating collars shall be below limits specified in the Product certificate. The criteria in NS 9415 does also cover the full combined systems, but there is no requirements for accreditation of an analysis of a full system.

The main reason for that the mooring analysis is the only analysis where accreditation is required, are to a large extend historically based. When NS 9415 was introduced in 2003 there was already a culture for performing mooring analysis, whereas for net pens there was a culture of using dimension tables, which were established from experience. However, recent years the net pen design has become more analysis based. At all locations with Hs > 2.5 meter or max current velocity above 0.75 m/s there are requirement for net pen analysis.

The required mooring analysis need to comply with NS 9415. NS 9415 requires a limit state assessment meeting the ultimate limit state (ULS) the accidental limit state (ALS), the serviceability limit state, (SLS) and the fatigue limit state (FLS). The accidental limit state includes predefined damaged conditions such as failure of mooring line.

Analysis of net pens, collars and all other parts need to be carried out according to the limit state principles, but NS 9415 is not as detailed on net pens as it is regarding the moorings. As an example there are no damaged conditions described explicitly for net pens.

THE EFFECT OF NYTEK AND NS 9415

Figure 3 shows annual fish escape from Aquaculture production facilities (fish farms) in Norway. As seen from this figure, the number of escaped fish has gone from an increasing trend to a decreasing trend with a pivot point in 2006. 2006 is three years after the introduction of NS 9415 and NYTEK regulations.

Figure 8 Number of escaped fish annually divided by production (Tonnes)

Figure 8 shows escaped fish relative to production. As seen from this figure the plummeting of fish escape recent years is even more profound counting it by the production volume.

From 2006, the directorate (FDIR) have statistics of fish escapes by cause. Three groups have been defined as

- Structural causes: Technical failure or design faults.
- Operation causes: Handling or similar action caused by man.
- External: Ships colliding with farm, sea mammals or similar.

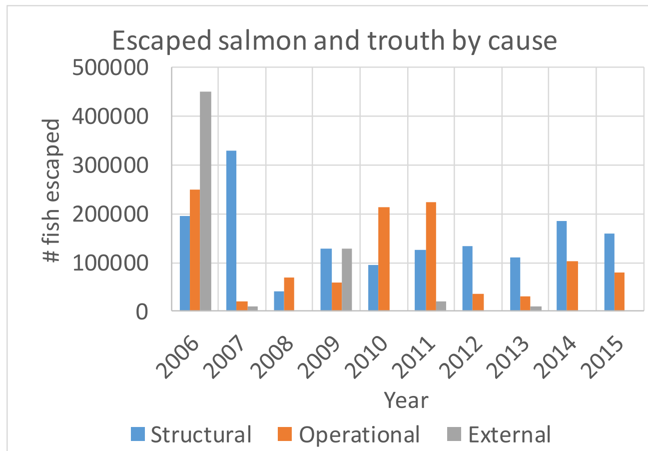

Figure 9 Salmon escape by origin (FDIR 2016)

Figure 9 shows fish escape by origin in the period from 2006 to 2015. Note that the figure only considers salmon and trout while cod is not included. As seen from the figure, escapes by external causes is large in 2006, medium in 2009 and neglectable the other years. In 2010 and 2011 fish escape by operations outnumbered fish escape by structural causes while in 2012-2015 the structural causes were the largest.

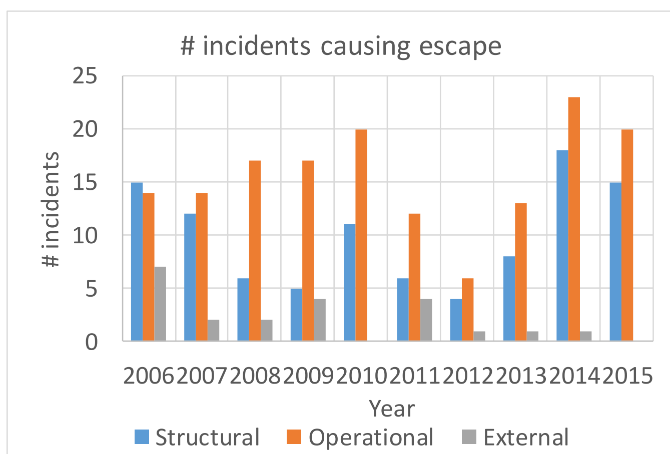

Figure 10 Number of incidents causing fish escape

Figure 10 shows number of incidents in each category causing the fish to escape shown in Figure 9. Also in Figure 10 only salmon and trout are the considered species.

As seen from Figure 10 the operational causes for fish escape outnumbers the other causes all years from 2007 and later. Note also that the number of incidents in total have an increasing trend since 2012. This corresponds with a time period where it has been an increase in adjustments to equipment, and introduction of additions to the net pens such as lice skirts, dead fish handling systems and other “small” adjustments. Also operations have increased in numbers and complexity for example in connection with delousing.

The overall trend that has been present from 2006 is that a lot of equipment have grown bigger. An example of this is the well boats which have grown significantly from 2003 until 2016. The well boats usually moor themselves to the fish farms during the operation of moving the fish from the net pen to the well boat. Analysis of such operation is shown in Figure 11. These vessels in 2003 normally was so small that the extra forces from them to the system did not give too large forces in the system. The increase of the size of the well boats, and not assessing operations by direct analysis and establishing a weather window for the operation, have resulted in an increase probability of damages to the system which consequently may lead to fish escaping.

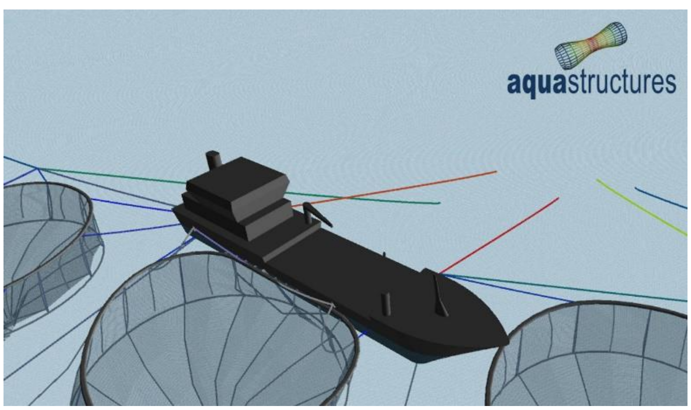

Figure 11 Operation of moving fish to live fish carrier. The vessel is normally attached to the moorings on the fish farm system.

One method of delousing fish is to introduce an impermeable net around the cage and then delouse by adding chemicals. Similar to lice skirts seen in Figure 12 such impermeable nets give different forces to the system than a normal net. If this is not considered in a direct design assessment, there is a risk for introducing forces that is larger than the design forces. A naval engineer will generally know this but it is not obvious for a fish farmer. This demonstrates the importance of clear rules, and criteria as well as understanding of the basic load effects applicable for fish farms. They are introduced in the next section.

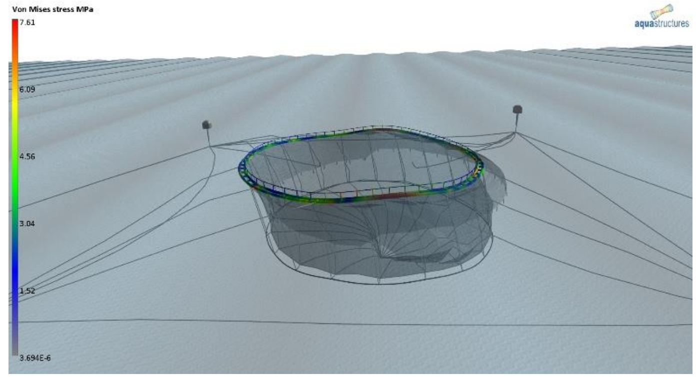

Figure 12 Fish cage with lice skirt. The lice skirt is located in the upper half of the net.

LOADS AND RESPONSES OF AQUACULTURE FACILITIES

Marine fish farms have a strongly flexible hydro-elastic behaviour. There are large geometrical deflections, occurring in components such as the net pens and the mooring lines, which again interacts with stiffer structural components. This section presents the main load effects to fish farm units denoted “drag loads” and “snap loads” and presents the way a response analysis need to be carried out.

Drag loads

A part of a fish net is shown in Figure 13. For such structure the Morison equation (Morison et al 1950, can be traced back to Lord Rayleigh) is an appropriate load formulation with the drag part of the equation as the dominating part. The force for steady flow acting on the fixed cylinder is expressed as:

$$F = Cd_{cyl}\frac{\rho}{2}dLv^2 \quad (1)$$

where F is the drag force, Cd_{cyl} is the drag coefficient for cross-flow to a circular cylinder, ρ is the mass density of water, L is the length of the cylinder, d is the diameter of the cylinder and v is the fluid velocity. In 3D, the velocity in Equation (1) can be interpreted as the cross-flow velocity which is the velocity in the plane of the cylinder cross section. v is the relative velocity between the fluid and the structure.

Figure 13 Typical net structure. This net is “knotless”.

The most important parameter used to describe nets is the term solidity (*Sn*). Several definitions are applied to this term. The most common formal definition is $Sn_{(mathematical)}=Sn_m = A_e / A_{tot}$, where A_e is the area casting shadow from a light perpendicular to the net and A_{tot} is the total area of the net.
For an ideal knotless mesh as shown in Figure 13 a mathematical expression for *Sn* can be formulated as:

$$Sn_m = \frac{d}{L_y} + \frac{d}{L_z} - \frac{2d^2}{L_y^2+L_z^2} \qquad (2)$$

Other definitions have been applied. Historically meshes were made with knots. This leads to higher solidity. A term having been used by e.g. Løland (1991) is:

$$Sn_{kn} = \frac{d}{L_y} + \frac{d}{L_z} + \frac{\Lambda d^2}{2(L_y^2+L_z^2)} \qquad (3)$$

where Λ is a constant typically 1 or 2. Yet another simplified definition is:

$$Sn_{2D} = \frac{d}{L_y} + \frac{d}{L_z} = Sn \qquad (4)$$

This is often denoted the "2D solidity" since it is based on adding diameters in both directions without subtracting for overlaying knuckle points or adding for knots. Knotless nets are sown as shown in Figure 13, meaning the net will not be "mathematically perfect". Hence the *2D* solidity can be a realistic definition of solidity and is denoted *Sn* in the further.

Because the flow must pass through a cross flow area smaller than the full area of the flow, the flow velocity must increase through the net in order keep the momentum of the flow. Normally a drag coefficient refers to the undisturbed fluid velocity. Doing so, Berstad et. al. (2012) showed that the relation between the drag coefficient of a single twine and the drag coefficient for the net membrane can be established as:

$$Cd_{mem} = Cd_{cyl} \frac{1}{\left(1-\frac{Sn}{2}\right)^3} \qquad (5)$$

Other variations of such relation have been presented. Figure 14 compares the above equation denoted Cd_mem with a couple of other variations presented in Berstad et al (2012) (Cd_mem_v2 and Cd_mem_v3). In addition, Cd_B1 presented by both Balash et al (2009) and Molin (2011) and Cd_KF presented by Kristiansen and Faltinsen (2011) is shown.

Figure 14 shows the relative difference on drag coefficient between a cylinder and a mesh as a function of solidity caused by the increase of the fluid velocity, since the flow must penetrate the net. It is seen that for 25 % solidity there is a 50% increase of drag relative to a cylinder. All relations shows that flow through a net leads to more drag than flow through a single twine which is well in line with empirical data (see e.g. Berstad et al 2012 and SFH 2010).

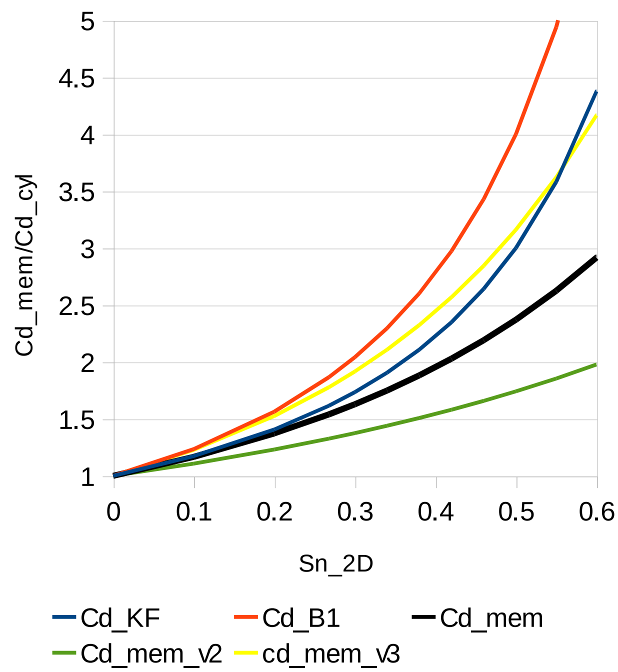

Figure 14 Comparison of different expressions for the drag coefficient, accounting for the increased velocity through the mesh.

Snap loads

A typical load mode for fish farm units are mooring lines and net pens going from slack condition to loaded condition. This causes an impact load to the rope attachment point. In this paper impact loads caused by ropes going from being unloaded to loaded is denoted a "snap load". To illustrate the physics for this, the most simplistic case, where such load can occur, is shown in this paper. This is the case seen in Figure 15 and Figure 16. Note that the case shown is a simplification for understanding the phenomenon.

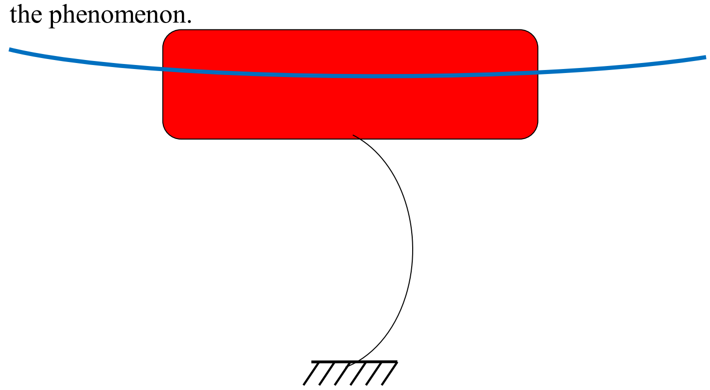

Figure 15 Float with slack rope

Note that in real fish farms the response causing "snap" loads is much more complex with many system degrees of freedom but the basic physics are the same as the cases seen in Figure 15 and Figure 16.

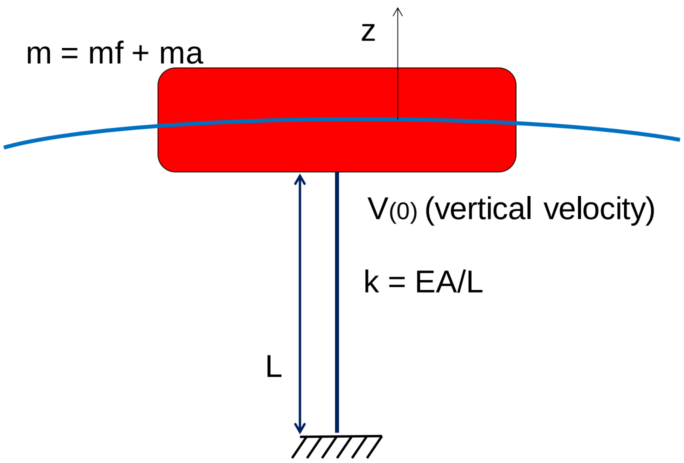

Figure 16 Initial value condition at moment rope goes stiff

m is the mass + added mass of the floater, and k is the stiffness being activated at the moment the floater rope goes from slack to tensioned. Neglecting the damping, the system can be solved by applying the classic impulse response equation for the motion:

$$z(t) = a\sin(\omega t) \tag{6}$$

where $\omega^2 = k/m$ and a is the amplitude of the impulse response. k is the stiffness of the system caused by the rope holding the float back like a spring: $k = EA/L$. This is a linear solution where the stiffness and mass is assumed to be constant. Note that the water plane stiffness is neglected. The velocity is the time derivative of the displacement can then be expressed as:

$$\dot{z}(t) = a\omega\cos(\omega t) \tag{7}$$

where $\dot{z}(t)$ is the vertical velocity of the system. In our case, we have an initial velocity v_0 in the z- direction which is the velocity at the initial time (t=0 exactly when the rope becomes stiff), expressed as:

$$v_0 = a\omega\cos(\omega t_{t=0}) = a\omega \tag{8}$$

This means the amplitude of the impulse response, a, is found as:

$$a = \frac{v_0}{\omega} \tag{9}$$

Now the relation between eigen period, mass and stiffness is introduced ($\omega^2 = k/m$) to:

$$a = \frac{v_0}{\omega} = \frac{v_0}{\left({}^{k}/_{m}\right)^{\frac{1}{2}}} = v_0\left(\frac{m}{k}\right)^{\frac{1}{2}} \tag{10}$$

This means that an impact as described above will introduce a harmonic impact response with amplitude a shown in the above equation. From the maximum response amplitude, the maximum force can be derived as:

$$F_{max} = ka = kv_0\sqrt{\frac{m}{k}} = v_0\sqrt{mk} \tag{11}$$

This means the maximum force is proportional to the initial velocity and the square root of the mass and stiffness. This is further described and validated in Aquastructures (2013).

Before t=0, assume that the velocity of the float follows the vertical velocity of the wave elevation as the wave builds up. Then v_0 can be found from the velocity of the vertical wave elevation at the moment the rope snaps. Assume a regular wave with amplitude. η. The wave elevation can according to airy wave theory (e.g. Faltinsen 1990 section 2) be expressed as:

$$\xi = \eta\sin(\omega_e t) \tag{12}$$

where ω_e is the wave frequency of encounter for the wave, this frequency has nothing to do with the eigenfrequency of the rope and float. At the time step $t = 0$ we get:

$$v_0 = \eta\omega_e\cos(\omega_e t_{t=0}) = \eta\omega_e \tag{13}$$

Introducing $v_0 = \eta\omega_e$, the maximum force F_{max} can be expressed as:

$$F_{max} = \eta\omega_e\sqrt{mk} \tag{14}$$

The above equations explain the susceptibility of short stiff mooring lines to mass objects, such as barges, since k is proportional to the rope stiffness and inversely proportional to the length. As seen by the above equation, shortening a rope by 1/100 will increase stiffness 10 times. Also using a chain with Elastic modulus of 10^{11} will introduce ten times the load as a rope with elastic modulus of 10^9, given otherwise equal response. Figure 17 shows max peak loads for the case seen in Figure 15 and Figure 16 calculated from Equation (11) and AquaSim respectively.

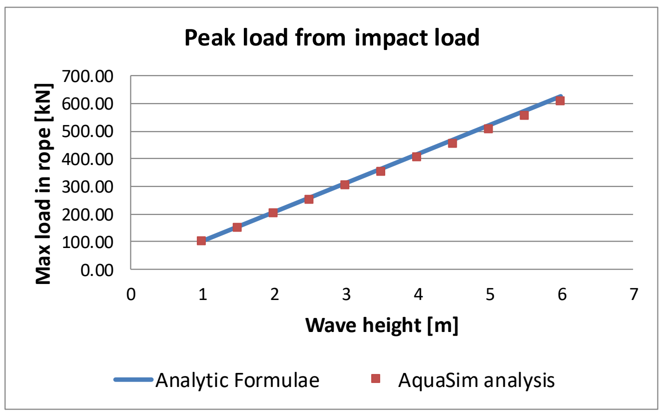

Figure 17 response by analytical formulae to AquaSim analysis.

Figure 17 shows results for an analysis model of the case seen in Figure 15 and Figure 16 compared to calculation by the analytical formulae (Equation 14). As seen from the figure results compare very well. From AquaSim analysis one can also obtain results for the response subsequent of the first impact.

This is seen in Figure 18 which shows the response of the axial load in the rope as a function of time.

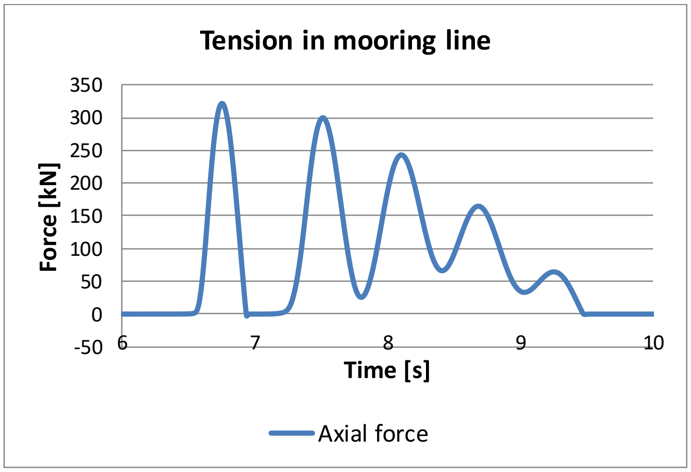

Figure 18 Tension in mooring line as function of time.

As seen from Figure 18 the first response peak is the highest caused by the snapping of the rope. After maximum response, the rope is offloaded to the point where it is slack again. This influence strongly the stiffness of the system such that the system will not have a linear impulse response. This is further described in Aquastructures (2013). Note that in order to capture such rapid response one need to have sufficiently small time increments in the numerical calculation of response. This system is underdamped. Damping of the system is neglectable for the max resulting response, but influence for how fast the succeeding response decay.

For real life fish farming systems, elasticity of moorings is often assured with “geometric stiffness”, which means flexibility is obtained by geometric changes to loads. This flexibility is equivalent to reducing stiffness by other means such as reducing the elastic modulus and/or increasing the length of the mooring lines. Normally the geometric flexibility is obtained by using chains close to the bottom and having buoys located in the mooring system between the net pen and the bottom attachment point of the mooring line. This is seen in e.g. Figure 1 and Figure 12.

Response

What characterize the response of aquaculture facilities is the combination of very flexible components, such as the net pens, the mooring lines and stiffer parts such as the floating collars, as seen in Figure 12.

The cage seen in Figure 12 has a normal net and in addition a “lice skirt” in the upper part. A lice skirt is an impermeable net installed to keep lice away from the fish inside the cage. Because of the impermeable lice skirt the loads to the net turns from being drag dominated, to be mass dominated since the fluid will act as added mass to the net. It will hence be susceptible for snap loads as described in the previous section. More regarding loads and response to impermeable nets in general case can be seen in e.g. Berstad and Heimstad (2015). The change in load pattern from a regular net to an impermeable net means structures containing impermeable nets are more susceptible for wear and fatigue of the net and connected ropes. This is important to account for in a design verification.

Moored barges are used to store the food for the fish as shown in Figure 19. For this case, the barge is a stiff large mass, and the mooring lines are soft parts. This means snap loads are highly relevant, and normally the design load for moorings and barge attachment point.

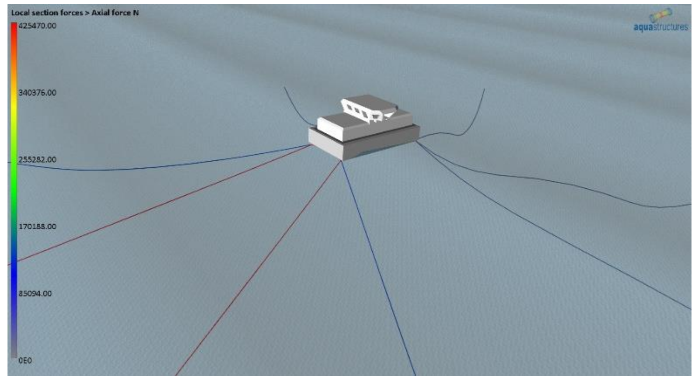

Figure 19 Barge containing the fish food.

This susceptibility for snap loads will also apply for operating conditions exemplified in Figure 2.

As seen from the load and response outlined in this section both loads and response is strongly nonlinear. Hence the feasible way for analysis is time domain simulation. Such analysis are normally carried out in AquaSim.

The AquaSim program is based on the finite element method. It utilize beam and shell elements with rotational 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.

$$\sum F = \mathbf{R}_{ext} + \mathbf{R}_{int} = 0 \qquad (15)$$

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 degrees of freedom (DOF’s). Equation 1 is then discretized as

$$F^{idof} = \mathbf{R}_{ext}^{idof} + \mathbf{R}_{int}^{idof} = 0, \quad idof = 1, N_{dof} \qquad (16)$$

where N_{dof} is the discrete number of DOF’s the structure has been discretized into. AquaSim deals with strongly nonlinear behavior both in loads and structural response. In order 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

$$\Delta\mathbf{R}^{i}(\mathbf{r}_{i-1}) = \mathbf{R}_{ext}{}^{i}(\mathbf{r}_{i-1}) + \mathbf{R}_{int}{}^{i-1}(\mathbf{r}_{i-1}) = \mathbf{K}_{t}^{i-1}\Delta\mathbf{r} \tag{17}$$

where $\boldsymbol{K_t}^{\boldsymbol{i-1}}$ 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

$$\bar{\mathbf{r}}_{j=1} = \mathbf{r}_{i-1} + \Delta\mathbf{r} \tag{18}$$

Based on this estimate for new displacements, both external and internal forces are derived based on the new structural geometry and the residual force, ***ΔR*** is put into the equation of equilibrium as follows

$$\Delta\mathbf{R}(\bar{\mathbf{r}}_{j}) = \mathbf{R}_{ext}{}^{i}(\bar{\mathbf{r}}_{j}) + \mathbf{R}_{int}{}^{i}(\bar{\mathbf{r}}_{j}) = \mathbf{K}_{t}{}^{i}\Delta\mathbf{r} \tag{19}$$

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 ***Δr***. Incrementing ***j*** with one, the total displacement is now updated as

$$\bar{\mathbf{r}}_{j} = \bar{\mathbf{r}}_{j-1} + \Delta\mathbf{r} \tag{20}$$

Now if Δr found from Equation 20 is larger than the tolerated error in the displacements, Equation 4 is updated ***(j = j+1)*** and Equation 20 is solved based on the new prediction for displacements, this is repeated until, ***Δr*** is smaller than a tolerated error, then

$$\mathbf{r}_{i} = \bar{\mathbf{r}}_{j} \tag{21}$$

i is increased with one, and Equation 17 is carried out for the new load increment.

At the default configuration, the program 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 commence. 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 (Newmark 1959, Langen and Sigbjørnson 1979). 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. Eggen (2000) which must be applied to handle 3D rotations in an appropriate manner.

Wave loads may be derived using the Morison formulae (Morison et al 1950) or using diffraction theory.

One form of diffraction theory used in AquaSim is a form of “strip theory” (e.g. Salvesen et al 1970), but in this case hull forces are derived by direct pressure integration over the mean hull surface (Fathi 1996). Diffraction loads may then be applied to beams or truss elements. Linearized values for diffraction, added mass and damping are derived for the elements mean wetted position. For irregular waves, linearized added mass and damping for the characteristic period in the wave spectrum are used in the calculations. Wave interaction between separate components is not accounted for. For a further description on how this is handled see Aquastructures (2006) and Fathi(1996). The other form of diffraction theory is 3D “source” theory applicable to impermeable nets.

For components that are small compared to the wave length the Morison Eq is normally applied whereas for larger components such as barges diffraction theory is applicable. When the Morison formulae is used, the cross flow principle is applied for beams and truss elements (see. e.g. Faltinsen 1990). 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.

Forces to the net mesh is calculated by using Morisons equation and adjusting the drag coefficient on a single twine by Equation (5). Forces from static internal and external pressure, current and waves to impermeable nets are calculated as described in Aquastructures (2015). The analysis of impermeable nets account for diffraction of wave loads (Aquastructures 2016).

PRESENT DESIGN VERIFICATION AND ANALYSIS CULTURE

As seen from Figure 7 both site survey report and mooring analysis are accredited documents. Under the present system the mooring analysis contains the following:

- Maximum axial forces in the mooring lines
- Requirement of holding power of the anchors,
- Maximum vertical force at end/anchor points.
- Resulting forces from the mooring lines to the floating collar
- Vertical forces into the floating collar.
- Fatigue calculations of the moorings if necessary.

Although most net pens are calculated with the same level of detail as moorings, there is no requirements for accreditation of analysis reports to the net pen analysis.

To find the response and force components AquaSim (e.g. Aquastructures 2006, 2012) time domain simulations are carried out. All simulations shown in this paper is from AquaSim. The analysis is carried out by first establishing static equilibrium in current, then regular og irregular waves are introduced and dynamic, hydroelastic analysis is carried out for as long as specified by the analyst.

As seen in Figure 7 the system for accredited design verification does not include operations as shown in Figure 2 such that engineering assessment like finding critical forces are based on professional judgement by the persons involved in the operations. NS 9415 does not limit any engineering assessment of operations to fish farm units and analysis have started to be implemented for operations.

NS 9415 AND THE NYTEK REGULATION, PLANNED REVISION

As shown in this paper there has been a huge developments in the Norwegian aquaculture industry since the last revision of NS 9415. It has therefore been decided to start a revision in 2017.

NS 9415 and the NYTEK regulations has in terms of reduced fish escapes been a success. However a lot of experience have been gathered since last revision giving a possibility to enhance the criteria in the standard.

One "hot topic" for introduction is operations, performed on the fish farm, and the establishment of weather windows, related to these operations. This may lead to a further reduction of the fish escape.

CONCLUSIVE REMARKS

NS 9415 and the NYTEK regulations along with the analysis and verification culture in the Norwegian fish farming industry have led to a significant reduction in escapes. By expanding the scope it is plausible that further reductions can be achieved.

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