General Analysis of Long-line Constructions used for Cultivation of Blue Mussels (*mytilis edulis*).

Arne Fredheim, Research Scientist

SINTEF Fisheries and Aquaculture

N-7465 Trondheim

Norway

Egil Lien, Senior Research Scientist

SINTEF Fisheries and Aquaculture

N-7465 Trondheim

Norway

Abstract

The technology used for the increasing blue mussel cultivation industry in Norway is mainly based on use of long-line constructions, which consists of long ropes, held up by buoyancy with collectors attached. The ropes can be from a couple of hundred to one thousand meters long, with several thousand meters of collectors attached. Earlier research has been limited with regards to the behavior of these constructions exposed to waves and current. Critical factors for the long-line constructions are initial tension of the line to avoid sagging between buoys, amount of excess buoyancy and the elasticity of the construction. SINTEF Fisheries and Aquaculture has developed a simplified 3D method to calculate the tension in and shape of these long-line constructions and submersion of buoys due to current loads. The method is based on making a model of the structure using rod elements and the Finite Element Methods. The shape of the collectors in current and the compression of the buoys when submerged are taken into account.

One important aspect related to these long-line constructions, is the risk of loosing buoyancy. If loosing one or more buoys, the adjacent buoys will be submerged, compressed and the buoyancy will decrease. This may cause a “chain reaction” where more buoys become submerged, which involve a decrease in buoyancy, and in turn might lead to a total collapse of the system. For a system using buoys with no excess pressure inside and with 30% extra buoyancy, the loss of two adjacent buoys might actually be enough for the total system to collapse.

Introduction

Present technology

The technology used for the increasing blue mussel cultivation industry in Norway is mainly based on use of long-line constructions, which consists of long ropes, held up by buoyancy with collectors attached. The different components in a traditional long-line construction are illustrated in Figure 1. The ropes can be from a couple of hundred to one thousand meters long, with several thousand meters of collectors attached.

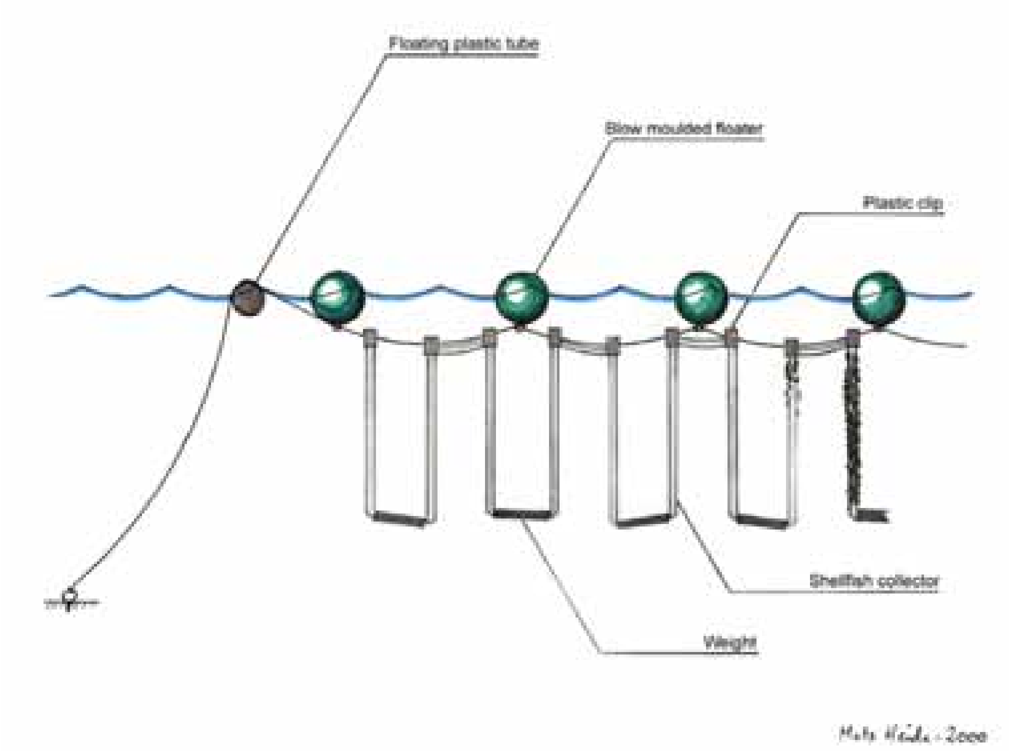

Figure 1 Illustration of the different components of a traditional long-line system.

In Figure 2, two of the most common constructions used along the Norwegian coast are shown. Earlier research has been limited with regards to the behavior of these long-line constructions exposed to waves and current. Critical factors related to the construction are initial tension of the line to avoid sagging between buoys, amount of excess buoyancy and the elasticity of the construction (consisting of material properties and geometrical elasticity).

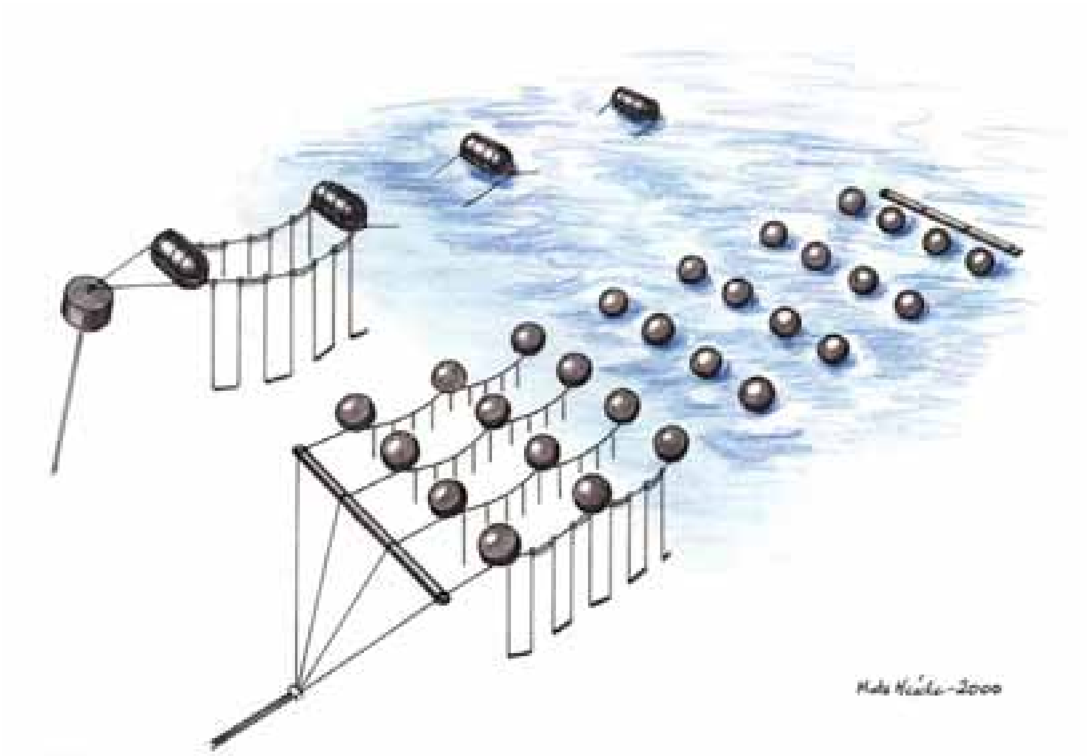

Figure 2 Illustration of the two most common long-line systems used in Norway.

The properties of a blue mussel farm change during its "lifetime", and this is a main aspect related to doing analysis of such a construction and also the operation of the farm. At the time when the spawns attach the weight of the collectors are small, the floats will be high in water and there will be a lot of sag and the whole setup will be very flexible. I.e. the load on the construction and its components are relatively small. At this stage it is a high risk of loosing the growth due to motion of the collectors when the construction is exposed to waves After a couple of years, the situation is different. The collectors are full (hopefully) with several kilos of blue mussel per meter. No the situation can be that there is to much weight on the collectors relative to the amount of buoyancy in the setup, so there is a risk that the complete long-line construction might sink. The latter is normally not a problem if the installation is moored to shore or at shallow waters, but in a Norwegian fjord with several hundred meter of waters depth, the process of rescuing such an installation is not a straightforward task. In the following some aspects related to theses issues and the blue mussel farms construction in general, will be discussed.

Methods

SINTEF Fisheries and Aquaculture has developed a simplified 3D method to calculate the tension in, and shape of, these long-line constructions. The method is a non-linear, quasi-static model without any dynamic forces included, and is based on modeling the setup with rod elements and using the Finite Element Method (Cook, 1995 and Ormberg, 1991). A rod element is an element that takes axial force, but does not take any bending moment. The geometry of the construction is established using catenary equations. The model is then divided into a number of elements and nodes for numerical analysis. The nodes have no physical dimension, but only represent a point as three co-ordinates. The element is represented with physical dimensions as length between the nodes, a cross-sectional area and also an elasticity module, *E*, which is a property of the material used in the construction (in this case the line). The unknowns are the axial forces in the rod elements and the co-ordinates of the nodes. The shape of the collectors in current and the compression of the buoys when submerged are taken into account. The forces acting on the system is calculated using ordinary viscous drag formulations, which can be found in any standard textbooks for hydrodynamic or fluid dynamic (Newman, 1977). Wave- and dynamic forces are not calculated. To solve for the unknowns an iterative solution scheme is implemented.

Drag formulation

The hydrodynamical forces are divided into drag ($\boldsymbol{F}_D$) and lift ($\boldsymbol{F}_L$) forces. The forces on each element are calculated from:

$$\boldsymbol{F}_D = \frac{1}{2}\rho C_D DL\,|\boldsymbol{U}^2|\,\boldsymbol{n}_D \tag{1}$$

$$\boldsymbol{F}_L = \frac{1}{2}\rho C_L DL\,|\boldsymbol{U}^2|\,\boldsymbol{n}_L \tag{2}$$

where ρ is the water density, C_D and C_L are the drag and lift coefficients respectively, D is the element diameter, L is the element length, $\boldsymbol{U}$ is the current velocity vector, while $\boldsymbol{n}_D$ and $\boldsymbol{n}_L$ are the unit vectors in the direction of the drag and lift force respectively. The forces are then transformed into the local co-ordinate system of the element and distributed half to each of the two nodes on the element.

A complete description of the construction is then achieved which consist of a set of nodes and element with properties attached, and the different loads on the system transformed into the node points. This will give us an equation system for which we can solve for unknown co-ordinates and forces using an iterative solution scheme. The Newton-Rapson iterative method (Cheney and Kincaid, 1991) is chosen, which is a common method.

Equipment

Buoys and floats

The purpose of the buoys or the buoyancy is to carry the weight of the ropes and the blue mussels. I.e. correct size, attachment and shape of buoys are critical for a safe operation of long-line setups. Archimedes discovered some 250 B.C. that an object submerged in water will have an upward force (buoyancy) equal to the displaced volume of fluid. For instance, 1

[m3] of water have a weight of 1 [tons] so an object, which displaces this amount of water, will have an upward force of 1 [tons] or 9.81 [kN]. Further the pressure inside and outside of the buoy has to be the same. Assuming that the temperature is constant, the relation between pressure and volume can be expressed as (Sonntag and Wylen, 1982):

$$P_0 V_0 = P_z V_z \tag{3}$$

where P is the pressure of the volume, V is the volume of the buoy, z is the water depth and 0 refer to the sea level. A standard buoy is made up of plastic material and will normally have a small excess pressure inside to keep its shape. In air the pressure is 1 [bar] or 100 [kPa]. The pressure in water will increase with the depth and at 10 [m] the pressure is increased to approximately 2 [bar]. Since the pressure inside and outside have to be the same, the volume according to equation 5 has to decrease. The volume at 10 [m] will then be half of the volume at the surface. In Figure 3 this relation between the water depth and the volume of the buoy due to the increased pressure is shown. And as seen the volume of the buoy decrease rapidly with depth, which is an important aspect to be aware of, since with large growth of blue mussels on the collectors, the buoys will be submerged and then the amount of buoyancy in the setup will decrease.

Figure 3 The graph show the relation between water depth and the effective buoyancy of a 200 [liter] buoy with an initial pressure of 1 [bar] at the surface.

Collectors

There are several different types of collectors in use; rope, "ladder", different type of netting, polyethylene band etc. In sea the blue mussel has a weight which is approximately 20% of their weight in air. With a seven meter deep collector and a density of 5 [kg] of mussel per meter after a couple of years of growth (normal in Norwegian waters), the load on the construction due to this one collector with blue mussels, will be approximately 69 [N]. With two collectors attached every meter of the long-line and with buoys every 10 [m], each of the buoys then has to carry 140 [kg]. With a minimum of 40% excess buoyancy, a buoy with at least 234 [liter] of buoyancy is needed.

The current force will highly depend on the amount of blue mussel on the collector. The amount of blue mussel will influence on the current force both directly and indirectly. First it has an influence on the size of the efficient drag coefficient and secondly the weight due to gravity forces will have an influence on the shape of the collector in current and thereby the effective exposed area of the collector to the stream. This last fact is illustrated in Figure 4, where the relation between the shape of the collector and the amount of blue mussel attached is shown.

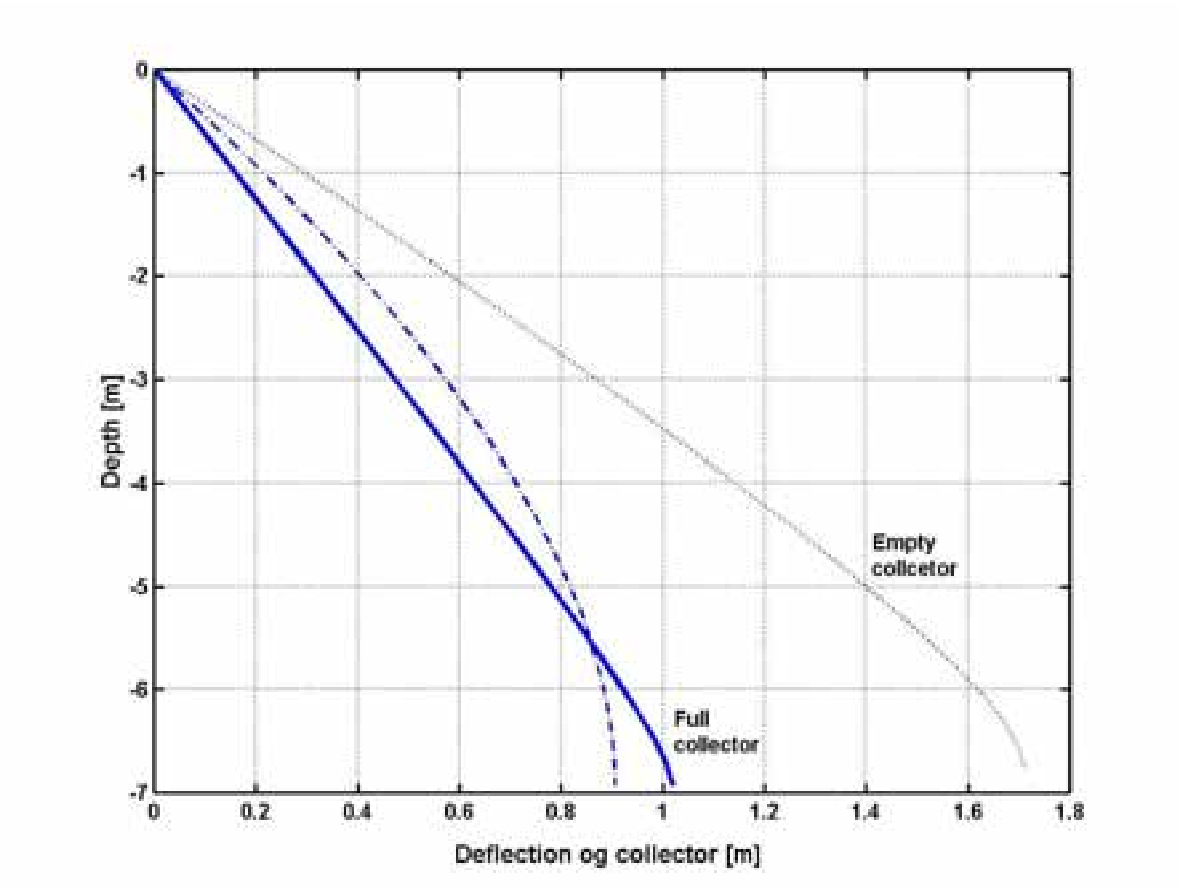

Figure 4 The shape of a collector in a current of 1 [m/s] with different amount of blue mussels attached. A full collector, solid line, medium full, long-dashed and en empty collector dashed.

Forces

Elasticity

The behavior of a structure due to external forces is dependent on the elasticity of the structure. The elasticity is a function of the ability of the construction and the material to deform. This is geometrical elasticity, due to the deformation of the construction and material elasticity, which is a property of the material used. The force in a line is a function of the elasticity, the cross sectional area and the deformation or the strain of the line according to the following relation $F = AE\varepsilon$. Here F is the axial force in the line, A is the cross-sectional area, E is the elasticity module and ε is the strain of the line. The strain ε is defined as $\Delta L/L$, where L is the length and ΔL is the elongation of the rope.

The amount of tension in the line is related to the elasticity of the system. Here is both the material elasticity and the geometrical elasticity important. The latter can be related to the deflection of the construction. To illustrate the importance of the elasticity and the deflection on the forces in the construction, the forces in a single line with different elasticity is used as an example. The example is illustrated in Figure 5, with at the top a line with the current direction parallel to the length axis of the line and at the bottom a line with the current direction being perpendicular to it. The calculations show that if the system is so stiff that the horizontal deflection of the line is less than 13% of the total length, the tension in the line will actually be larger with the current in from the side, than with the current along the line.

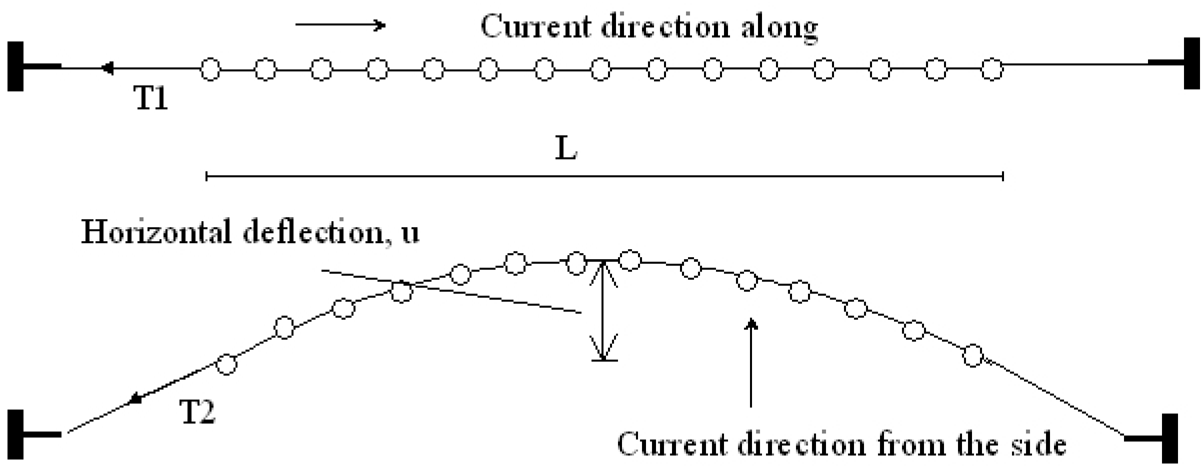

Figure 5 If the deflection u/L of the line with the current direction from the side (bottom) is less than 13% of the total length L, the tension T2 in the line will be larger than the tension T1 when the current direction are parallel to line (top).

Current forces

Besides the weight of the blue mussel, it is the current, which impose the largest loads on a long-line system. Normally the relation between the current velocity and the current force is quadratic. Due to the large flexibility of the structure in a long-line setup, the relation is no longer quadratic, but rather more linear. In Figure 6 the tension in the long-line are shown for different current velocities. As seen in the figure the relation has a linear characteristic.

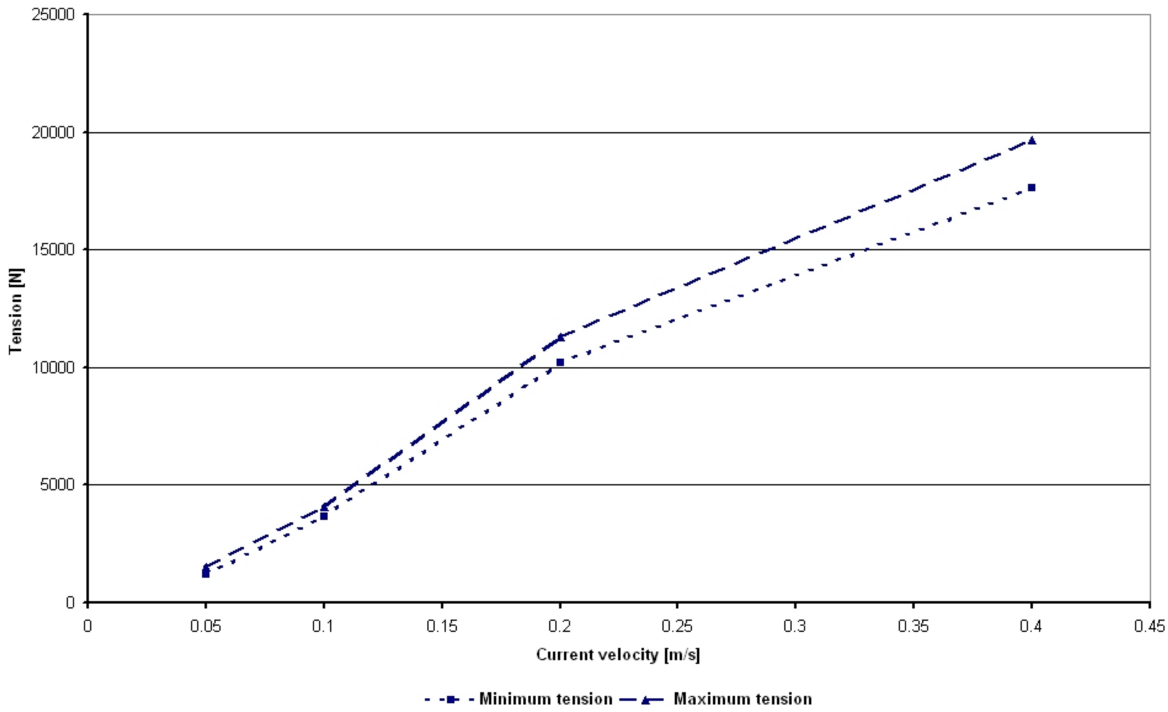

Figure 6 Relation between current velocity and tension in the long-line. As seen from the figure, the relation has a linear characteristic.

Case study

Here is presented, as a case study, calculations on an installation with ten parallel long-lines. Each of lines has a length 220 [m], and is connected together at the end with the use of floating tubes (this long-line setup is illustrated in Figure 2.). The modeled setup has mooring lines of 150 [m] at 50 [m] of water depth and end tubes with 420 [liter] of buoyancy. An average weight of 140 [N/m] along the line is assumed. At every 10 [m] buoys with a capacity of 200 [liter] are included, which give excess buoyancy of 30%. It is also assumed that the buoys are only air-filled with no excess pressure inside.

First a single line with a pre-tension of 1.5 [kN] is looked at. The distance between the buoys and the amount of excess buoyancy in the system are varied. What consequences this has on the risk of collapse for long-line system is then considered. The mechanism is that if one buoy is lost, the buoys adjacent to this will become more submerged due to an increased load on these (less total buoyancy in the setup). Thereby due to the relation described earlier, the volume of these adjacent buoys will decrease due to an increase in external pressure (see Figure 3). If the mussel farm setup is not properly adjusted, loosing of one buoy might start a "chain reaction", where adjacent buoys are submerged and loosing buoyancy, which again will might lead to even more buoys being submerged. The final consequence of this "chain reaction" can be that the complete long-line are lost, due to not enough excess buoyancy. This mechanism is illustrated in Figure 7.

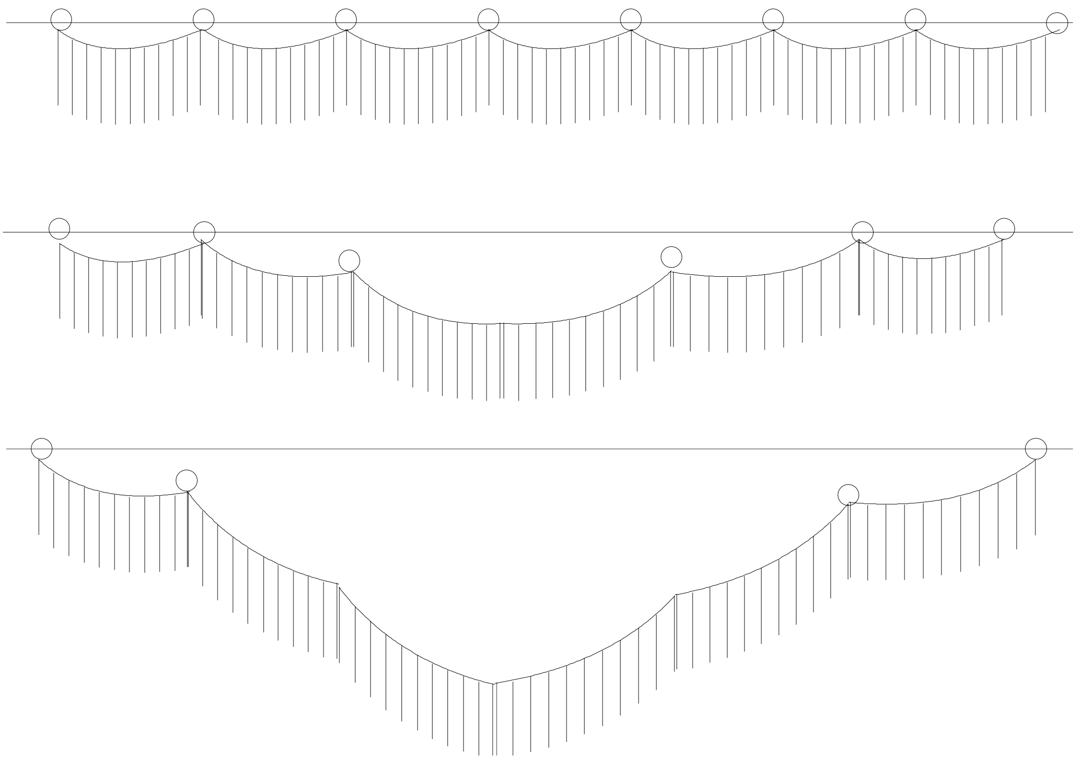

Figure 7 At the top a long-line with all buoys intact. Then one buoy is lost and adjacent buoys are then being submerged, line two. If there is not enough excess buoyancy in the system, a "chain reaction" might start where even more buoys are being submerged and loosing buoyancy.

In Table 1 the results of the parameter study looking into how many adjacent buoys that initially are needed to be lost, before the complete line are submerged are presented. The results are presented as a function of excess buoyancy in the setup and the distance between the buoys. As the results show, in some situations even the loss of one or two buoys might be enough for the complete line to be submerged and lost.

Excess buoyancy	**Distance between buoys**		
	2.5 [m]	**5 [m]**	**10 [m]**
30%	***3***	***2***	***1***
40%	***4***	***3***	***2***

Table 1 Number of adjacent buoys on a long-line that initially, if lost, will result in a total loss of the line. The results are presented as a function of excess buoyancy in the system and distance between buoys.

If looking at the complete blue mussel farm setup, with ten parallel lines and the floating end tubes, the situation is similar to what is described previously. The system can be looked up on as ten individual long-lines connected together with an extra large buoy at the end. For this discussion, the end tubes are assumed to have a buoyancy of 420 [liter], which should be representative such a blue mussel farm setup. The mechanism is the same as previously described, by loosing a few adjacent buoys it is possible to lose a complete long-line, but this extra buoyancy at the end of 420 [liter] are actually not enough to carry that extra weight from the line. The consequence of having this floating end tube is that if one single line is lost, this extra weight will pull down the complete system and all the ten parallel long-lines with all the blue mussel production are lost.

Conclusion

What here is hopefully illustrated is how important it is to know of and understand the mechanisms involved when dealing with any kind construction. Even with what at a first glance seems to be a rather straightforward construction, such as a blue mussel farm consisting of only buoys and ropes. As shown, actually in some situation loosing only one or two adjacent buoys of maybe several hundred buoys in total, might be enough to sink a large blue mussel farm. Of course a lot of these issues, can be solved through good operation and management of the farm and by investing in reliable and correct equipment. It is for instance possible to use floats with excess pressure inside or to use other types of equipment for flotation than buoys. And also if the water depth is not too large, sinking of the farm might not be a big problem after all. But unfortunately other types of equipment than ropes and buoys, are often more expensive in the short run and a lot of the companies involved in blue mussel farming are relatively small and have limited resources.

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