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Offshore mariculture: Mooring system design[†]

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SUMMARY – The development of cage culture systems need to be understood as a function of a number of different structural and operational elements. The design and installation of mooring systems for marine aquaculture units is a very critical element in the establishment of reliable and effective production systems. Based on careful assessment of site conditions, and an appreciation of cage system characteristics and farm operating requirements, suitable mooring specifications may be developed. This process is particularly important for offshore mariculture, where environmental loading may be far more demanding. This paper reviews the engineering aspects of mooring marine aquaculture systems with respect to potential site conditions.

Key words: Mooring, mariculture, offshore aquaculture.

RESUME – "Mariculture en mer ouverte : Conception des systèmes de mouillage". Le développement des systèmes de culture en cages est dépendant d'un certain nombre d'éléments structurels et opérationnels. La conception et l'installation de systèmes de mouillage pour des installations d'aquaculture en mer est un élément critique dans l'établissement de systèmes de production sûrs et effectifs. Un cahier des charges des mouillages peut être déterminé après une étude approfondie du site ; une appréciation des caractéristiques des cages et une étude des besoins opérationnels de la ferme. La mise en place de ce cahier des charges est particulièrement importante dans le cas de la mariculture en haute mer, pour laquelle la pression environnementale est beaucoup plus importante. Cet article passe en revue les aspects techniques des systèmes d'aquaculture marins flottants ; et expose les grandes lignes des performances en fonction des conditions potentielles du site.

Mots-clés : Mouillage, mariculture, aquaculture en pleine mer.

Introduction: The development history of cages and sites

Intensive finfish cage culture has shown considerable expansion from Norway and Scotland into the Mediterranean, North and South America. The Far East is showing a similar trend though growth in Northern Europe, from where much of today's technology has originated, has more recently slowed down. The variety of species under cultivation has also increased, still usually the higher value species, requiring an extended knowledge of stock and cage system interaction. Research and pilot trials are proceeding in many countries on other species. Sites as sheltered as the original marine cage culture locations are becoming limited, due to pressures from tourist development, urbanization, marine trade and the consequences of environmental lobbies. In some cases, inshore sites have also proved to have lower stock growth and higher disease rates, with greater risks of contamination from overuse, and from other activities. As a consequence, notable expansion is now taking place in what may be designated as coastal areas, maybe 0.5-2 km offshore in depths of 20-50 m.

These areas are characterized by more severe wave climates, as well as greater constraints on access and workability. It may not be possible to get to the site on some days, or if possible, the prevailing wave climate can make husbandry difficult, slower and potentially more dangerous. Better boats and properly trained crews are needed. Diving and maintenance operations are also more difficult. Feeding must often be carried out by automatic feeders, or by service boats equipped with a feed cannon (see also Beaz Paleo *et al.*, this volume; Cabello, this volume). Perhaps most importantly, the engineering of the cages must be much more sophisticated, and stronger, to cope with 24 hour exposure to waves. Maintenance also becomes much more vital to maintain the security of the installation.

[†]With additional material developed by J.F. Muir, editor.

The sea is perhaps the most difficult environment for engineering, and a fish farm, like an offshore oil rig, represents perhaps the most difficult of structures to deal with. The sea can generate great storm forces on any floating or seabed mounted structure, and storm events occur randomly, although with a long term probability structure. A ship can run for shelter to a harbour, whereas a fish farm cannot. The constant 24 hour per day bending, compression and tension within structural members, are optimum conditions for fatigue. Similarly constant motion in a corrosive fluid are ideal promoters of mechanical wear and corrosion. Repairs and salvage are more difficult, and in some cases, access may be denied to some structures during a storm. Though it is has been the case that initial insurance premiums for a cage farm are high, reducing with the years as the risk is seen to be less uncertain, losses can often be relatively unlikely in early years, but risks increase after neglected maintenance or when component fatigue has set in.

A plastic circle site in Scotland was abandoned because feeding was only possible on a limited number of days per year. A Farnoccean cage site was abandoned because the feed hopper was too small to permit fish to be fed for the full duration of periods when the hopper could not be refilled. Cages in Malta are boarded by driving a small boat hard onto the flexible hose buoyancy tubes, so that its bow over-rides the tube. A large fish barge off Ireland was so dangerous to board on many days, that personnel ultimately jumped from a small boat launched from a larger boat. The relative motion between the deck of larger boat and the cage decks was as much as 4 metres in certain conditions.

Diverse cage technologies

A particular feature of the last 5 years has been the introduction of many different cage designs, intended to cope with the more rigorous conditions in the coastal zone (see also Scott and Muir, this volume; Christensen – practical development of offshore mariculture systems: the Irish experience, this volume; Basurco *et al.*, this volume). Steel fabricators redesigned, enlarged and joined together square cages in galvanized steel. Plastic pipe manufacturers entered the field with various cages; with a lower capital cost they survived greater wave climates for longer periods, if properly installed and moored. Suppliers to the oil sector used hoses designed for the transfer of oil under offshore conditions to withstand even greater wave climates. Semi-submersible cages, very large rigid floating barges, rotating cages and tension spar cages have also entered the field. As knowledge increases, cage design for a given wave climate may well converge, but this is not the case for the present.

Most of the above cage types are totally surface oriented; their floating collars must respond to the incident wave profile. Movements and accelerations are much greater, daily, and during coastal storms. This requires much stronger components, and more maintenance. Due to such limitations, and also the need to operate in deeper waters (>100 metres), Tension Leg moored systems are now being considered (see also Lisac, this volume). This technology is successfully used in the offshore oil industry, in some of the world's most extreme wave climates. This system can be simply described as a buoyant structure, with low waterline area, or even submerged, which is moored by a series of long vertical cables or (tendons) to a seabed template (mooring system) which resists the buoyant uplift. This system can respond readily to horizontal components of wave particle orbital motions, without response to vertical components of motion. Thus it has very low resistance to wave loads, and consequently low internal loads, and an environment less likely to cause fish abrasion within a net enclosure. However, a number of practical husbandry issues may still require to be resolved.

Between the vastly differing cage designs there are large differences in capital costs per tonne of biomass accommodated. In general, higher capital input offers longer life in bigger waves, and often a decrease in operating costs, particularly for labour. However, the financial consequence of risk may be greater with high capital cages. In a market where technology is advancing fast, low capital strategies may have an attraction, provided they can generate profit. Historically, some designs have been relatively successful, others were capital intensive disasters. Some succeeded in surviving the wave climate, but destroyed the fish during severe storms. Others rapidly fatigued and broke up, while some were simply impossible to work. In all case, mooring designs have been a critical element in the operating and longer term performance of cage systems. Key issues are discussed as follows.

Mooring design: General notes

Moorings are required to hold cages against the forces generated by wind, currents and waves, and to allow the fish stocks, and the cages and nets the best chance of survival. These aims are not

always compatible; a mooring designer can offer moorings which will never fail or break; however, they may hold the cage so rigidly in position that the cage or nets break, or the fish are swept against nets, and die through abrasion, de-scaling and osmotic trauma. In higher offshore wave climates, there have been losses due to fish being swept out, over the top of the cage handrails.

In sheltered waters, requirements to moor a cage safely were minimal. This has changed dramatically with moves into coastal waters, and a potentially much higher wave climate (Kery, 1996). Mooring failures were commonplace in the early days of coastal farming, but a better understanding of the problems, and more sophisticated analysis has largely reduced these risks. Perhaps the most important point is to view the cage group, its nets and moorings, as a single system, whose components are mechanically linked. Their dynamic responses cannot be considered in isolation, each component affecting the other.

Some manufacturers have attempted to design a standard mooring system for their cage groups, which if not catering for likely maximum conditions, is totally impractical. Cage and mooring design is "site specific", and careful and combined choice of cage type, nets and most specifically moorings, has a considerable bearing on the ability of fish stocks to survive in major storms, on exposed sites.

Nets and net drag

When wave orbital particles move through a system, and when there are currents, nets generate loads which have to be resisted by the moorings. While current loads are relatively steady, wave particle motion loads are reciprocating, within fairly short periods. The nets will always try to respond to water movements, while the cage collar, having more mass, is likely to move very differently. This can generate significant strains on the cage collar or handrails, such that either nets tear, or the handrails are deformed. This is particularly so with heavy, large cage groups or multi-pen barges.

There have been many disastrous losses due to nets ripping on large multi pen barges, and large heavy collar pens. In some cases the solution has been to de-couple the nets, by fitting float lines to the nets, leaving the connections to the collar loose. Due to these losses, marine insurance Classification Societies, such as DNV, BV and the Salvage Association, have produced classifications for fish farm nets, which are based on the wave climate of the site. However, these should also take into account the type of pen. While strong tidal or steady currents may be good for improving water quality, in streams of above 1 knot, they present increasing problems with net deformation. Without weights, the nets may deform so much that there is insufficient volume for the fish. Even with weights or other anti-deformation systems, the upper limit for nets and fish survival in most cage designs is 2½ knots, although some sites are exposed to 3 knots, or perhaps more.

Mooring design for a specific cage system and site

Wind and current forces are proportional to the square of the velocity. Thus an increase in current from 1 knot to 2 knots will generate 4 times the drag on a rigid submerged body. Wave forces are much more difficult to compute, because the dynamic response of a system depends on so many factors. A change in the mooring system will change the internal loads on the cage system. This is a complex topic, but in general a mooring system should be designed not only for specific cages, but also for the expected site conditions of water depth, wind, waves and current.

Location and orientation of the cage group

The choice of location and orientation of a cage group is usually a compromise between conflicting goals. The following aims may be involved:

(i) *Conform with the available tease area*: this may be placed to permit continued use of a navigation channel, or to keep the site from view of a popular beach, it may be granted without respect to shelter for the farm. It might be chosen to align itself with the shoreline, or to avoid areas of scientific interest.

(ii) *Minimize storm wave loads on the moorings and cages:* by obtaining whatever shelter can be afforded from known risk conditions, and aligning structures to present the least resistant surface.

(iii) *Locate cages so prevailing wind wave motions are minimized for husbandry:* while the former may require alignment relative to the worst storm waves, the latter may be oriented toward prevailing winds from a different direction. Some types of cage groups are best positioned with the axis pointing into the storm sector, others with the axis at right angles.

(iv) *Maximize water depth under the cages:* to avoid or reduce the higher forces created by shortening, stepping waves in shallower water, and reduce the incidence of breaking waves; also to maximize the dispersion potential of settling and soluble wastes.

(v) *Minimize distance to the shore base:* this frequently conflicts with the water depth objective, and with lease area constraints. It is always better to place cages in the deepest water practical.

(vi) *Configure cage groups as close together as possible:* if multiple cage groups are to be used, this generally means that moorings will have to overlap, particularly in the desirable deeper water depth. This leads to difficulties of installation and maintenance, and can lead to abrasion failure.

(vii) *Minimize mooring costs:* this often means placing cages in the shallowest water, or where there is good sediment for drag embedment anchors. It is often in conflict with most of the above aims!

Generally in site waters <40 metres deep, cages should be placed in the deepest possible area, to offer the maximum security, and the least environmental impact. Most fish farms start with a modest installation, and expand by stages. It is most important to plan the areas for expansion in advance, so that the early installations do not impede future development.

Calculation of wind and current forces acting on cage structures

These loads are deemed "steady" loads by the designer, as they are generally of constant strength and direction for periods of more than 30 minutes, which permits loads to be fully transmitted throughout a system, right down to the anchors. In contrast wave loads are reciprocating and varying in strength sinusoidally over periods of seconds, and the system rarely has time to take up a "steady" position. The designer must work with predicted maximum conditions, even though the chance of them being combined is generally of lower probability.

Wind loads and wind pressure

As noted, wind exerts pressure on the exposed (above water) components of the cage system (see also Turner – offshore mariculture: site evaluation, this volume). Although wind speeds fluctuate in the short term, it is generally sufficient to use predicted 15 second gust windspeeds, to compute steady structural forces. These are around 90% of the normally tabulated 3 second gust windspeed. Table 1 below shows wind pressure exerted by various windspeeds on a square metre of surface at 90° to the axis of the wind direction.

Table 1. Wind velocities and pressure forces

Beaufort force	Force 2	Force 4	Force 6	Force 8	Force 10	Force 12	50 year
Windspeed (knots)	~5.0	~13.5	~24.5	~37.0	~51.5	~68.0	~77.7
Windspeed (m/sec)	2.6	7.0	12.6	19.1	26.5	35.0	40.0
Wind pressure kN/m ²	4	30	96	223	426	751	981
Wind pressure kgf/m ²	<1/2	3	10	23	44	77	100

Exposed cage area

It is then necessary to sum the surface area exposed on a given cage type, by measuring the dimensions on a scale elevation plan of the cages, for which a planimeter can be helpful. However, the

areas of cage "hidden" in the elevation, such as the back side of a plastic circle, and its handrails, must also be added into the calculations, as wind pressure will be exerted on all above water surfaces.

Different wind directions

Major storm winds will usually arrive from specific directional sectors; there are also, often different prevailing wind sectors (Shellard, 1965). The designer is principally interested in the storm maxima, and their expected (highest probability) direction, but should also take into account that storm maxima may occur from other directions. It is usual therefore to apply the storm maxima to the cage group for a number of different directions. For most exposed areas, fixed mooring are used; the cage group will not rotate, and unless completely symmetrical, will present different areas to the winds from different directions. Depending on the symmetry, and the wind statistics, the designer may choose to look at different directions in these ways: (i) if sheltered from waves say, for a 180° sector, analyse the windloads for the other 6 x 30° sectors; (ii) if not sheltered, analyse for all 12 x 30° sectors; and (iii) if the structure is rectangular, but with a similar vertical profile throughout, analyse axially, trans-axially, and at 90° to the diagonal.

Shadow effects

Some areas of a structure will shadow other areas, so that less wind speed, and therefore wind pressure is generated on the sheltered structures. Detailed procedures are available for taking this into account, which can be consulted elsewhere (Rudi *et al.*, 1988), but for simpler assessments, an allowance may be made on the estimated reduction of wind velocity created by sheltering effects.

Current loads and current drag

The general equation for current drag is $F_x = \frac{1}{2} (C_x \cdot \rho \cdot A_x \cdot V^2)$ expressed in kN. The terms in the equation are C_x , the drag coefficient, ρ the mass density of seawater (in t/m³), A_x the area normal to the flow (in m²) and V the incident current velocity (in m/s). The drag coefficient depends on the shape of the object, the wetted area, and surface "roughness". Drag coefficients are also modified by shallow water, relative to the depth of the structure, and can be accessed from tables which tabulate the result of various trials, with different shapes (e.g., Herbich, 1992).

Wind driven currents

Wind driven surface currents can be approximated by taking 2% of the hourly mean wind velocity. These should be added to the tidal currents from the survey data, to give the true maximum storm current.

Net solidity factor

A net of given mesh, and knotted or knotless construction can be assigned a "solidity factor" which is the ratio of the area of twine, to the total area of a panel of net (see Carson, 1988; Rudi *et al.*, 1988; Beveridge, 1996).

Area exposed to current drag

Similarly to the calculation of wind pressure, the designer has to break down the underwater structure into components, and calculate the drag force on each component separately. However, some components can be regarded as "rigid" for the purposes of analysis, while others, such as nets and moorings, will deform progressively with increasing current speeds. The amount of deformation will depend on the amount of net weighting installed.

The drag force on the rigid components are summed to give the total drag, for a given current velocity and direction.

For the given current speed, the net force on a single panel of net, has been established by Milne (1970), Osawa *et al.* (1982), Woods Hole Engineering Associates (1984) and others. The nets behind

a single front panel held rigidly in a vertical frame, are progressively sheltered, and subject to less current, by deformation of the current streamlines around the cage group. The total drag of a row of cages, for a given relative current velocity vector may be established by the following (see also Loland, 1993; Beveridge, 1996):

(i) Calculate bottom and side panels separately with a drag Coefficient C_d of 1.

(ii) Choose a mean drag coefficient for the transverse panels, according to the predicted net angle to the current flow. (0° -0.1; 15° -0.3; 30° -0.8; 45° -1.2; 60° -1.5; 90° -1.7) (Kowalski and Gianotti, in Rudi *et al.*, 1988). The chosen angles will depend on the scale of the current, and the amount of weighting chosen. However, if we assume that an initial angle of 40° is a maximum practical deformation to retain sufficient volume in a cage net for fish survival, then we can graduate the other nets back up towards 90° , assuming a velocity/force reduction factor.

(iii) Use a force reduction factor k of 0.8, corresponding to velocity reduction at each net of say, 10%, to calculate the force on each net. Sum these for the total number of nets.

This is just one method which might be used for calculating net drag, shown above for illustration. There is now further published trial data on net deformation and current drag, which can be accessed to give a more direct result (e.g., Loland, 1993; Beveridge, 1996). Account should also be taken of the fouling of nets (and the cages and moorings) by marine growth, which leads to significantly increased drag forces. In areas where nets are likely to be significantly affected, it would be wise employ a safety factor.

Calculation of wave forces acting on a cage structure

Both the likely highest waves over a 50 year period, and the prevailing or average wave heights are important. The former may cause instant total failure, and the latter will promote gradual failure or reduced life, through fatigue. The prevailing wave climates will also affect the ease with which day to day operations can be accomplished. Accurate wave climate prediction is essential for the design and choice of cages and moorings, suitable to withstand the environment on a given site, for a "reasonable" life. All methods of wave climate prediction have ranges of accuracy, due to limitations of data. It is important to take into account the probability of worst scenario possible maximum waves.

The calculation of wave forces is the most complicated of the mooring designers calculations (e.g., Dean and Dalrymple, 1991). Without examining this topic at highly detailed level, key concepts and general principles are described below, and some examples given of the necessary calculation steps. Further sources of information include Marintek (1987), Oltedal *et al.* (1988), Rudi *et al.* (1988), Cairns and Linfoot (1990), Beveridge (1996), Gace *et al.* (1996), Kery (1996).

Drift force and orbital motion

Perhaps the most important concept is the relationship between the forces on a cage, and the moorings which restrain the cage. An object floating without restraint in waves (assuming zero wind and current, and zero mass) will move in a manner which can be split into 2 components of motion. These components are a relatively small, steady drift motion in the direction of propagation of the waves, plus a periodic circular motion superimposed upon it. Moorings act as a restraint on the floating object, and their "elasticity" or stiffness is critical in determining the resulting motions and forces (e.g., Lien *et al.*, 1996). Greater mooring "stiffness" will produce greater mooring restoring forces.

It is often said that a fragile glass light bulb thrown into violent storm waves, will survive, because it is not restrained. In contrast, an object rigidly located, such as a breakwater, or a ship aground on rocks, is subject to very large forces, and in the case of ships aground in large storm waves, will rapidly break up. A consequence of this, is that a mooring designer may have to choose different moorings with different elastic properties, before finding the properties which may reduce the forces on cages, and mooring restoring forces to a minimum.

Wave drift force

This depends to some extent on the incident wave spectrum, but a simple conservative estimate of wave drift force can be made, without recourse to modelling the structure, by assuming that all waves are fully reflected off the structure. In an irregular sea, the mean drift force is given by the equation:

$$F_{wd} = \rho g L H_s^2 / 16 \quad (\text{for regular seas the divisor becomes } 8)$$

where L is the length of element, H_s is the significant wave height.

Wave induced motions: 6 degrees of freedom

Any floating object will respond to wave motions. However, it will not in general follow exactly the wave profile, due to its own inertia and mass. The greater the ratio of residual buoyancy to mass, the more closely will the object follow the wave profile, and the more violent its motions may become in a storm. An object moving in space is said to have 6 degrees of freedom. These correspond to translation along the 3 mutually perpendicular axes, and rotation around those axes (Fig. 1). These translations and rotations are referred to as:

<i>Translations:</i>	<i>Axis:</i>	<i>Rotations</i>
1 Surge	Horizontal axis	4 Roll
2 Heave	Vertical axis	5 Yaw
3 Sway	Horizontal trans-axial	6 Pitch

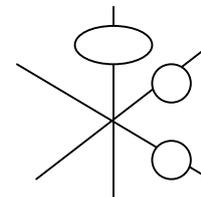


Fig. 1. Axes of movement.

Response amplitude, and RAOs

How rapidly, and to what extent a floating structure responds to the orbital particle motions, depends on the structure, and the incident wave parameters. The response of a vessel or floating structure can be defined in terms of Response amplitude operators (RAOs) which for a given wave frequency, or length, give the ratio:

$$\frac{\text{amplitude of motion of structure}}{\text{amplitude of wave motion}}$$

Simple estimates of RAOs can be either made from data collated for similar structures, or by tank trials or mathematical modelling. Various research institutions have carried out trials on simplified fish farm structures for a few cage manufacturers, although this has rarely extended to newer experimental concepts, and regrettably not to the many cage copyists. Clearly response is different for free floating, and moored structures, and this must be taken into account.

Actual amplitude of motion can be approximated by first determining waves' forces on a fixed cage, and then by determining the forces on the cage system when forced to oscillate in calm water with the same period as the wave, and with the same amplitude.

It is unusual to have the financial opportunity to carry out tank trials on a particular structure, and it is common to use of proprietary computer programs, for calculations. In addition designers will make use of experience, and simple means of assessing the "liveliness" of response, or simply use a conservative response amplitude in excess of 1, in order to calculate the maximum mooring restoring forces generated by waves of maximum storm parameters, by a given set of moorings. Simple "rule of thumb" methods of determining the response include looking at the vertical area presented by floats to incident waves, and calculating the ratio of residual buoyancy to mass. The former suggests how much total refraction will occur, and the latter gives a simple view of likely vertical response.

Excursion diagrams

A useful design tool is the Force – Excursion (offset) diagram. This is a graph or equation, which plots the horizontal movement of a mooring, against the increasing restoring force of the mooring. The components which rise from the anchor on the seabed, up to either the cage or a cushion buoy, are

referred to as risers, in the UK. These may be off all chain, or part chain, and part man made fibre rope. In addition, the mooring designer may place a heavy section (either a short length of heavy chain, or a weight) part way up the riser, to maintain tension, and vary the Force-Excursion characteristics of the riser:

(i) Chain excursion diagrams: Risers made from all chain, or all rope, have different Excursion Diagrams. The geometry of a chain suspended from 2 points some distance apart, has the general equation, of $y = c \cdot \cosh(x/c)$, where y is the vertical axis, and x the horizontal. The characteristics of any all chain mooring, from line tension, horizontal restoring force, chain angle with the surface, can all be plotted from 2 input parameters, the depth of water, and the weight per unit length of the chain. A characteristic of an all chain mooring is that it can be pulled the first unit distance horizontally with little force, but the force for subsequent unit distance excursions increases, until at small chain angles relative to the surface, an almost infinite load is required to gain a further excursion.

(ii) Rope excursion diagrams: rope risers generally have a straight line excursion diagram, provided the rope is operating within its elastic limits. Some man-made fibres, such as polyamides have relatively high stretch before their yield point (i.e., the point at which the line no longer returns to its original length after de-tensioning), and others (polyesters, polypropylenes) have relatively low stretch. The rope construction also plays a part (see Beveridge, 1996; Kery, 1996; Lien *et al.*, 1996).

Combination risers: Opposing risers

Combined risers have a rather more complex excursion diagram, which is a matter of number-crunching, assisted if there are models of "standard" riser combinations to speed up problem solving. A further complication is the pre-tension which must exist in opposed moorings, if the excursions are not to be very large. This means that in any direction (axial or trans-axial, there is a combined excursion diagram, where the pull of the mooring on the opposite end is taken into account.

International standards

There many International, European and National standards relating to various topics of marine engineering, and specifically to mooring of floating structures. Their preparation has been in response to the demands of insurers, and professional associations, driven by the many failures which have occurred historically. Many branches of marine engineering have had to break new ground, including such areas as harbour and marina construction, ship design, and the offshore oil industry. As a "sunrise" industry, with as yet a limited profitability, these standards have rarely been applied directly to mariculture.

On one insurance claim for a fish farm, relating to storm damage, the eventual legal battle for payment focused on the standard used to design the fish farm cage, and whether or not it was applicable to such a structure. At the time of writing the legal arguments are still proceeding, some 6 years after the event...

However, several standards are now directed specifically at fish farming, and Det Norske Veritas, and the Salvage Association have produced a number of classification rules for fish farms. Also, while not specifically directed at aquaculture, a large number of rules and standards have been more generally introduced, which will also have an impact on the "insurability" of present and future installations. These standards are sometimes out of date with current technology, or not very rigorous, and at other times so general as to be inapplicable. Nevertheless, they have an impact both legal, and with regard to the perceived financial security, for external investors and Insurers, and must therefore be taken into account. However, there is a limit to the analysis which can be carried out, given the present low profitability of fish farming. As loss of life, as opposed to loss of capital equipment & stocks is rarely an issue with fish farming, a less rigorous approach is normally adopted.

Quasi-static mooring analysis

A mooring design can either be the result of a quasi-static mooring analysis, or of a full dynamic response analysis. The latter is normally carried out using proprietary software on a medium sized computer (e.g., Marintek, 1987). Which is better depends largely on the range of errors of the techniques, and on the amount and accuracy of input data. A well analysed quasi-static analysis will be much better than a dynamic study performed with limited data. Any study based on measured data, or tank trials will also in general be more accurate. If either is subject to model calibration,

post-monitoring and analysis, then the probability of survival must be enhanced. The general steps in quasi-static mooring analysis are as follows:

- (i) The mooring geometry and mooring excursion/force equations are defined.
- (ii) The mean environmental force is applied to the system, and the excursion (offset) calculated.
- (iii) The periodic wave forces, and response amplitude is now applied to the system.
- (iv) The line tensions resulting from this maximum excursion are now calculated.
- (v) These line tensions are now compared with the minimum breaking load of the riser components.
- (vi) The maximum peak anchor loads are calculated for each riser, and direction.
- (vii) A safety factor (generally 2) is introduced in to the riser strengths.
- (viii) The maximum peak line loads are recalculated with 1 line broken, or after a line failure.
- (ix) If the proposed mooring specification fails the safety factor test, then a new specification is tried.

This type of mooring analysis is most common, and documented by many sources. In addition, it is endorsed by a number of insurance classification societies. However, it is open to errors through the lack of sufficient, or accurate data, and particularly through under-estimating wave climate. Also, a mooring system which may survive, could still be so "stiff" that fish stocks are killed through abrasion, or nets torn, during violent storms.

Wave phase differences

On the peak of a wave system, the water is moving rapidly in the direction of propagation of the wave, and equally rapidly in the opposite direction in the trough (orbital wave particle motions). Wavelengths in any kind of a wind (from say Force 3 upward) typically range from 10 m, up to as much as 200 m in long duration (24 hours +) gales. If the wavelength is less than the length of a multiple cage system, then some points of the system will be subject to water moving in the direction of the waves, and other parts will be subject to water particles moving in the opposite direction. In this situation, the forces on the system as a whole, (as opposed to single cages), cancel out, at least to some extent: (i) in a hinged steel cage system, this will lead to alternate tension and compression loads; and (ii) in a flexible plastic circle cage grid system, this will lead to cages moving within their grid squares.

In the former, this can lead to buckling stresses, and high hinge loads, as well as "Whiplash" effects in long cage systems. In the latter, if grid square sizes are not adequately large, this can lead to contact between cage nets, and the grid ropes, with possible abrasion damage to, and breaching of the nets.

Breaking waves: The breaker zone

When waves approach shallow waters (relative to their wavelength), they are progressively slowed by bottom friction. This process can be calculated by iterative mathematical wave modelling. This phenomenon leads to the reduction of wave velocity of propagation, and of wavelength. The wave period remains the same. Finally, when the waters are shallow enough, the wave will eventually "break", with the wave crest water particles overtaking the lower water particles. The beach gradient, and the incident wave parameters define whether this process is quite violent (plunging breakers), with a rapid release of energy, or relatively less violent (spilling breakers) with a slower wave energy release. In general a long flat shallow gradient underwater shore, will have a wide breaker zone, where waves of different parameters will "break" at different distances offshore. In contrast, a steep underwater gradient will confine the breaker zone to a relatively small band:

(i) Plunging breakers release considerable energy, and are capable of major destruction of floating structures. Their influence is the major cause of headland erosion. It is vital to situate a fish farm outside plunging breakers.

(ii) In some areas where the incident storm wave periods are less than 5 seconds, it may be possible to use floating breakwaters to attenuate incident waves. Floating breakwater technology is becoming more adventurous, and a number of new concepts have been advanced within recent years. These may prove successful with attenuating, or diverting longer wave period waves in the future.

Forces due to operations and berthing of vessels

During routine husbandry, and sometimes during the introduction of juveniles, relatively large boats will be berthed alongside cages. In the farming of salmonids, large well boats of more than 35 metres overall length may be used. In even relatively light winds, waves and currents, especially alongside light cages such as plastic circles, the loading effects of farm workboats, or well boats can lead to the design loads for the moorings being approached, or the cages being damaged:

(i) As cages move further offshore, and larger boats are required, this situation will get worse. Fixed floating structures move in a very different manner to a boat, and the differing dynamic response between the two can be frightening. Several fish farm sites have been abandoned, not because the cages and fish were unable to survive, but because they could not be economically worked. This has been due to the difficulties of getting boats alongside, or personnel on the cages, for feeding or husbandry. The advantages of using helicopters for oil industry personnel can be well understood.

(ii) Offshore fish cages will need large feed stores, and automated feed systems, which can be filled by boats "hanging off" on a single line mooring and filling hose, as tankers pumping offshore oil.

Mooring geometry

Moorings are often popularly thought of as ships' permanent moorings, or temporary anchoring. However, these are usually "swinging moorings", where the vessel will adopt the line of least resistance to incident wind and current conditions. Permanent moorings are also generally placed in very sheltered positions relative to a fish farm, and a ship can also run for shelter to a harbour. By contrast, a fish farm will be subject to the worst weather that can occur, 24 hours per day, 365 days per year, and must maintain its station, and orientation. Not only do moorings have to be much stronger than those for a ship, but they also have to have much greater allowances made for mechanical wear and corrosion.

Fixed location and orientation moorings

The simplest type of "fixed" mooring is a double mooring, secured to either end of a floating system. This however can generate huge loads when the environmental forces act across the principal axis of the system. The next simplest system is to use a number of moorings, arranged like the spokes of a wheel, around the platform. However, the most commonly used system today is that of 4 orthogonal pairs of moorings. This system has a number of advantages which are compared with the other 2 systems below (Fig. 2). Table 2 outlines some of the key issues.

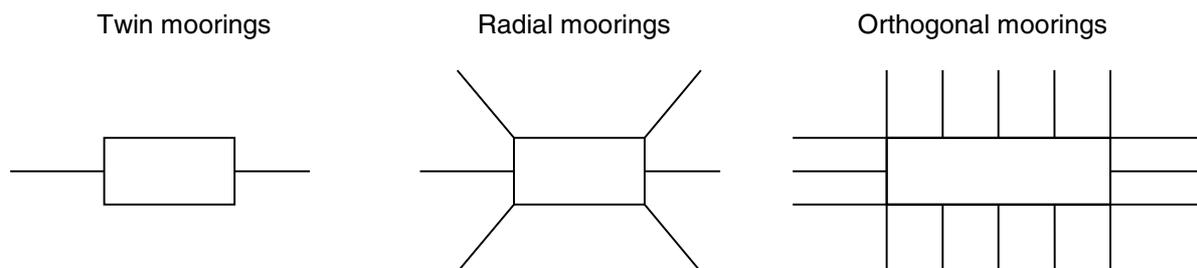


Fig. 2. Cage mooring layouts.

Table 2. Comparison of cage mooring types

Mooring geometry	Pros	Cons
Twin Moorings: "Fore & Aft" (2)	Simple	Very high trans-axial loads: very heavy anchors: low redundancy
Radial moorings: (6-10)	Simple	Rotation: high riser loads: big anchors needed: low redundancy
Orthogonal mooring: 4 x (3+n)	No rotation: low riser loads: small anchors: high redundancy	More risers

Orthogonal mooring geometry

There are a number of other advantages with orthogonal mooring geometry, apart from those noted above. With a hinged or flexible structure, the extra moorings provide lateral support, and reduce internal loads, either on hinges, or in the case of a grid of cages, on the end moorings. Also, when drag embedment mooring anchors have to be "proved" by pre-loading, opposed moorings can be tensioned one against the other by a relatively small winch. This avoids the need to use a very large tug, to generate pulls of 10 tonnes or more.

Downward mooring loads: Cushion buoys

Because anchor lines are not infinitely long, they make a downward angle with the horizontal plane of the (still) water surface. Heavy chain moorings, generate static downward loads. These must either be supported by the buoyant cage collars, or by separate cushion buoys. When horizontal loads act on the cage system, the downward load on the cushion buoys will be increased, in proportion to the tangent of the angle between the mooring riser below the buoy, and the surface:

(i) In strong currents, winds and waves, some cushion buoys may submerge. This can lead to buoy failure under compression, and a progressive loss of buoyancy. In deeper water, it is often difficult to maintain a small down angle between riser and surface, as this would require very long lines.

(ii) If submerged grid mooring systems such as are used on Polar Circle cages, are too small, then the downloads on the cage collars can become so large that significant portions of the collars become submerged in heavy weather. This greatly increases drag, and may lead to collar damage.

Mooring components

Whichever type of mooring layout is employed, a number of elements need to be assembled together, correctly specified and installed, physically and operationally compatible with each other, and effective in use and maintenance. Key elements include the anchor or mooring unit on the seabed, the rising line, which connects the anchor to the surface system, and the surface or subsurface mooring grid. The major elements comprise several smaller sub-units – particularly links, shackles, droppers, safety lines, buoys, etc., which in effect are integral in the complete system. Details of various mooring components may be found elsewhere (e.g., Beveridge, 1996; Kery, 1996; Lien *et al.*, 1996,) and are not discussed extensively here. The following sections briefly summarize key points.

Anchor specification

A range of different types is available, commonly from the shipping/fishing industry. Major options are usually between gravity or dead weight devices – mooring blocks or mass anchors, which rely primarily on their weight, and those which rely on their ability to wedge into the seabed substrate (drag embedment). In some cases, gravity devices are also able to hold into the seabed, through suction forces as they settle into soft bed materials. Anchoring efficiency, based on the ratio of holding power to the weight of the device varies widely with the ability of the anchor to grip, and is thus closely dependent on seabed materials. Blocks are widely used because of their simplicity, their stability to tension in all directions, and their relative ease of positioning and relaying, but their efficiency is low. In some cases, dragging of blocks in storm conditions may be problematic, but this can sometimes act as a "partial failure" safety factor in extreme conditions. Gripping devices are much lighter and more

efficient in the appropriate substrates – e.g., muds and shingle mixes, but need to be properly tensioned; once bedded in they can also be difficult to reposition. In some cases, experimental active embedment anchors such as screw devices, piles, vibration anchors and water jet or explosive embedment devices have also been considered (Kery, 1996).

A complete cage system was once reported to have disappeared, presumed to have been stolen in its entirety. Diving on the site revealed the farm's concrete block gravity anchors had slid down an underwater clay slope, dragging the farm down with them. The farm had stopped on a level area with the anchors in some 40 m of water. However, the farm, and nets were still intact, with the weighted nets still containing fish.

Rising line components

A range of materials and configurations may be used, the most common of which involves a chain section at the lower end of the line, a synthetic rope in the main upper length, and various elements of buoyancy or weighting to adjust the profile of the line, and its response geometry when subject to varying load (Lien *et al.*, 1996). A range of different types and specifications may be available for chain and rope (e.g., Beveridge, 1996; Kery, 1996). Key issues concern weight and tensile strength, elasticity (length change with applied tension), stretching, dimensional wear, degradation. Float units need to be specified according to volume and shape, and to their resistance to deformation when submerged (Lien *et al.*, 1996).

Mooring grid components

The use of rope or cable-based mooring grids simplifies the attachment of cage units, providing a stable and dimensionally secure framework, to which a number of temporary structures may also be attached. Properly designed and with strength-compatible components it is important in its ability to dissipate stresses through its flexibility, reducing the risks of concentrating stresses in individual cage structures. For light and flexible cages, such as plastic circles or "Flex-float" systems, this makes it possible to attach cages with near-horizontal lines, without significant vertical forces acting against the limited buoyancy of the cages. The ability to detach and move individual cages without disrupting the positioning of other cages in a group is also advantageous. Rope or cable elements require to be specified at standards equivalent to those for the risers; connectors such as shackles, links, connector (node or monkey) plates and patent rings, and flotation buoys to support the horizontal framework, are all very critical. These need to be set up securely, with good access for inspection and adjustment, if needed. A sufficient degree of redundancy should be included, as far as possible, so that the grid retains some degree of safe function if damaged or separated. Where more deeply submerged grids are used (e.g., in tension leg systems) it is even more important to ensure these are well designed and securely assembled, as routine maintenance will be less simple.

Sourcing suitable materials

It is important to ensure that materials used for moorings are of the appropriate manufacture and quality, and where relevant, are properly tested and certificated. New components from reputable marine equipment suppliers are the most clearly dependable, but salvage materials, e.g., anchors, chains and cables from ship-breaking yards can be cost-effective and secure, if checked and tested.

Installation methods and plant required

The installation of mooring systems is an important aspect of the overall development of a cage site, and requires to be planned with care. Individual mooring components for a large cage system can be substantial in size and weight, and the total materials required can be involve the movement of significant loads, to the farm site and from there to the installed position. The supply of materials from diverse sources may require considerable logistic planning, and it will be important to ensure that this is well co-ordinated. Key elements/stages include:

(i) Working base: a suitable and secure area for storing and laying out the mooring components needs to be identified – ideally a level, surfaced area, such as a workyard, parking ground or dock area, adjacent to the intended site. Lockable containers are useful for temporary secure holding of valuable materials and components. Assembly tools, welding gear and other equipment is usually also required. If mooring blocks are to be made on site, suitable formers, cement and aggregate storage,

concrete batching and compacting equipment, or good local suppliers of ready-mixed concrete will be needed.

(ii) Workboat or mooring vessel: capable of moving and positioning the mooring components, and operating in the expected site conditions (see also Beaz Paleo *et al.*, this volume). A towable or outboard-mounted mooring barge is also useful for towing out heavier components, and acting as a secondary working platform. Smaller boats are also useful for general access, checking positions, crew transfers, etc.

(iii) Cranes: dockside and on mooring vessels – capable of lifting and moving the mooring elements safely at the required horizontal reach. This is particularly critical for floating cranes, whether on vessels or barges, to ensure stability in working sea conditions.

(iv) Access: – for materials to be taken to the assembly areas, for mooring components to be taken safely to the intended cage site.

(v) Marking out: key locations in the mooring site can be marked out on a hydrographic chart, checked on site with GPS or conventional optical surveys; local transect markers can be identified, and temporary positions marked with light lines and floats.

(vi) Making up moorings: the mooring lines and grids need to be adjusted to length and assembled to form the appropriate sub-components, which would then be finally linked together on site once the anchors are laid. Primary work can most easily be done on shore, using temporary measure lines or markers to help lay off the line lengths. Further adjustments can be done at sea, and all components and connections given a final check (preferably by someone else from those who had made up the system) before installation.

(vii) Laying anchors and risers: if blocks are used, these can be set at the intended site, using positioning co-ordinates to define the location. For embedding anchors, these should be dropped a suitable distance outwards (i.e., opposite the direction of tension) from the place of intended location, and tensioned inwards to their final position. The setting distance will vary with the substrate, but would typically be at least same distance outwards as the intended depth, though it is better to err on the longer rather than shorter distance. If the anchor does not set within the intended distance, it is better to restart than to bring it too far inwards, thereby steepening the riser angle excessively. Laying of moorings and lines should be done carefully, taking particular care not to foul anchors with riser line, to tangle or snag the line, or to endanger staff.

(viii) Anchor proving: the anchors, once set, need to be tested to the intended tension level. For opposing moorings, this can be done using a winch on board a vessel, barge or cage assembly to tighten up on either side. Alternatively, the pulling power of a larger vessel can be used. If possible, a load gauge should be used to check the working tension.

(ix) Tensioning the rising lines: these need to be finally adjusted to ensure that the cage and/or mooring assembly is correctly and evenly tensioned around its axes. This can be checked by the position of the central structure (cage or grid) relative to the riser lines, by the vertical and horizontal angles of the lines, or by the levels of riser floats – which if lying too high or low would indicate that the line is too slack or tight respectively.

(x) Diver swim of rising lines: finally, it is very important to check the whole system visually – to ensure that blocks or anchors are cleanly placed and/or embedded, that lines are lying properly and are not kinked or tangled, and that connections are sound.

Mooring maintenance

Cage moorings are a dynamic system, which must respond to motion, under load, every minute of the years it is installed. Maintenance is critical, to ensure that components are physically sound and that linkages are secure. Critical dimensions of items subject to wear – chain links, brackets, shackles, splicing eyes, need to be checked periodically, bolts and shackle pins need to be tightened, and riser lines may need to be adjusted. The anchors, and lower components of cages whose moorings are in more than 50 metres often cannot be inspected economically by divers, and in some cases may have to be lifted. In the very deep waters of British Columbia (>300 metres) some mooring lines were more

than half a kilometre long. The attendant in service stretch, and maintenance problems have consequently been very great. Other points include:

(i) Considerable redundant strength (over sizing) must be built into components to ensure that they have a reasonable life before requiring replacement.

(ii) Meaningful routine mooring inspection is vital. Many inspection protocols are simply a "placebo" for insurers. In order to be useful, a mooring inspection must measure existing component strength, and compare it with the design strength. It must also forecast wear or deterioration which may occur during the interval; to the next inspection. SEAWORK uses in-house tables which predict the strength of worn components.

With a rigorous and effective system of maintenance of both cages and moorings, with clearly defined parameters for replacement or repair, a well designed and installed system should be capable of reliable and secure operation.

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