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Aquacultural Engineering 38 (2008) 145–160

aquacultural engineering

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Review

The physics of open-water shellfish aquaculture

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Received 8 November 2007; accepted 28 January 2008

Abstract

Aquaculture of shellfish species is expanding in many countries. Limitations on, and competition for, inshore water space is making offshore shellfish developments more attractive. Here we review issues relating to the design and mechanics of shellfish longline structures in relation to the offshore marine environment. Two main facets are explored: (i) the effect of the flow (waves and currents) on the farm and (ii) the reverse perspective of the impact of the farm on the flow. Because these systems are relatively new, we first examine similar systems, both natural (kelp beds) and man-made (floating breakwaters, fish farms). Techniques for measuring both the local oceanography and the structural response are listed along with new approaches for measuring important properties. A number of future applied research topics are identified as being a key to advancing the industry, including issues like mooring design, vertical drag coefficients, wave–current interaction, stratification and influence on fauna.

Keywords: Shellfish; Physics; Oceanography; Longline; Mussel farm; New Zealand; Waves; Currents

Contents

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doi:10.1016/j.aquaeng.2008.01.006

1. Introduction

Shellfish aquaculture has a long history, with many early societies extending their wild harvesting techniques through the introduction of accessible artificial substrata and transplanting of important species. This early development occurred because shellfish larvae have a free-swimming stage. Hence, provided there is a suitable supply of juveniles and nutrients and that the environment is not too extreme, a harvestable crop will result. Given these determinants, provision and development of a suitable substrate is a major factor over which some control can be exerted. Here we review the physical factors associated with open-water shellfish aquaculture. There is inevitably a local bias. However, the New Zealand industry is a useful template as it is well established but still expanding and one that place a high value on environmental sustainability.

Here we define offshore as being exposed to substantial oceanic conditions—mainly in the form of exposure to large waves and storms. As there have been few shellfish developments to date in this environment we consider ‘‘open water’’ shellfisheries—those that are at some distance from shore and require reasonable infrastructure. This broader category includes developments in large bays and coastal inlets.

Many inshore techniques for sustaining shellfish have evolved through individual ingenuity and adaptation. These tend to have regional idiosyncrasies. Within South East Asia the main species grown is *Perna viridis* and open-ocean aquaculture is being trialled in a number of countries including Malaysia, Indonesia, Thailand, Cambodia and the Philippines. The largest producer in the world China (FAO, 2004) grows predominately *Mytilus galloprovincialis.* This species is also grown across much of Europe, the Russian Federation, Brazil and Australia (Gosling, 2003; Buck et al., 2006). *Mytilus edulis* also known as the blue mussel is grown in parts of Europe, North America and Scandinavia. New Zealand, the forth largest mussel producer, grows an endemic species *Perna canaliculus*.

A variety of methodologies have evolved to produce shellfish in large quantities in inshore waters. Rafts and longline techniques have been established in tandem with mooring and harvesting approaches. Strategies have also been developed to deal with things like ice-cover (Drapeau et al., 2006) and large tidal ranges (France). In addition, recruitment is no longer left to chance and collection of juveniles (spat), integration onto the artificial substrate and harvesting are important steps in the evolving methodological development. Intensive farming of inshore locations highlights a range of areas of potential usage conflict (Ridler, 1997): aesthetic value, navigation, nutrient/phytoplankton depletion, space allocation and the likelihood of terrestrially sourced contamination. This combination of issues had led to industry looking to offshore waters for future expansion.

Moving into exposed offshore coastal/ocean waters requires substantial investment in planning and infrastructure. One only needs to look at the oil industry to see the scale required and the importance of good engineering for successful development of infrastructure in the ocean environment. Two complementary facets to the engineering of such marine structures arise. First, the effect of the flow on the structure controls the structural survival and the environment the crop must develop in. Second, the effect of the structure on the flow is also important for correct assessment of environmental impact, especially through its influence on redistribution of waste and nutrient-depleted water. Clearly, there is feedback between the two. Section 2 describes approaches to shellfish aquaculture in open waters, Section 3 describes comparable canopy systems, Section 4 describes the effect of flow on the farm, Section 5 describes the environmental implications of such structures and then Section 3 synthesises the findings.

2. Approaches to open-water shellfish aquaculture

Currently, there are a number of different types of mussel farm design, which vary depending on the water depth, hydrodynamics and the regional style. These include surface and submerged longline farms and raft-based structures (Fig. 1).

The continuous longline technique is becoming a dominant farming style and can be used for any of the main mussel species commercially grown around the

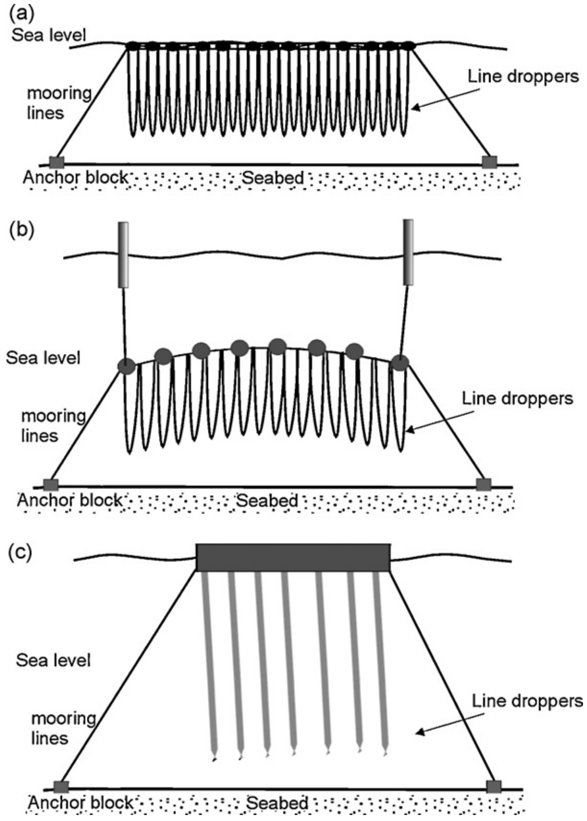

Fig. 1. Different styles of "open ocean" shellfish farm including (a) surface longline, (b) submerged longline and (c) raft development. In (a) and (b) the float-line combination is the backbone of the longline.

world, e.g. *Mytilus galloprovincialis, Mytilus edulis and Perna canaliculus.* Longline farms typically cover 3–100 ha (0.03–1 km^2) and consist of up to 200 longline of approximately 120 m in length, each consisting of two parallel "backbone" ropes supported by buoys (Fig. 1a). Culture ropes (line droppers) are looped continuously from the "backbone" rope and can be up to 5 km long depending on the water depth. Descending from each end of the "backbone" ropes are mooring lines connected to anchor blocks that are typically fixed into the seabed. A number of countries (e.g. Canada, Australia,) use a longline system consisting of individual line droppers for the harvest of *Mytilus galloprovincialis or Mytilus edulis* (Fig. 1a), suspended from the backbone towards the seabed rather than one continuous line running along the length of the backbone. In South East Asia (e.g. Malaysia, Cambodia) as well as using the longline system *Perna viridis* is cultured offshore using wooden poles imbedded into the seabed onto which the mussels attach. In Cambodia these poles are also used to hold strings on which seaweed is cultured similar to the traditional French methods.

The longline technique is becoming the dominant approach to physically supporting a substantial crop with the minimum of infrastructure. In open-ocean areas with strong waves and currents a number of countries are developing submerged mussel farm culture. The degree of submergence of the crop lines can be achieved through buoyancy control (e.g. Norway, http://www.smartfarm.no) or through mooring design (e.g. USA Grosenbaugh et al., 2002). Submergence reduces visual impact as well as the degree of influence of surface waves (Fig. 1b). It does make harvesting more difficult but not prohibitively so, with specialised vessels set up to manipulate the backbone and strip and re-stock the line. A submerged longline resembles that of a surface longline except that it is suspended 5–10 m below the sea surface by cable attached to large buoys sitting on the surface at each end of the longline (Fig. 1b). Some approaches keep the floats along the line sub-surface as well. Another open-water technique is raft culture (Fig. 1c, also Blanco et al., 1996), which in many respects is similar to longline culture. As with some longline culture, ropes are suspended from the raft. The rafts are square shaped and usual vary between 100 m^2 and 550 m^2 in size. Rafts are usually made of a series of wooden or plastic cross frames. A range of other species can also be matured in suspended culture including oysters (e.g. Pilditch et al., 2001) as well as seaweeds (Romo et al., 2001).

3. Comparable canopy systems

Offshore shellfish aquaculture physical science is relatively new and little-studied so there are substantial benefits to be gained from looking at other canopy systems. Whilst the most obvious comparative system are fish cage arrays (e.g. Cromey et al., 2002; Fredriksson et al., 2005; Hartstein et al., 2006) there are a number of other canopies that are more relevant in size and outlay including, for example, kelp beds and floating breakwaters.

Offshore natural kelp beds have a number of points in common with open-water shellfish structures. They are subject to offshore conditions whilst supporting some type of suspended canopy. A major point of difference is that in a kelp bed there are many separate structural entities individually attached to the seabed as opposed to the end-point attachment of a longline. On the other hand "crop densities" are similar with a kelp bed having around 0.01 individual plants per m^2 (Jackson, 1984) and a shellfish farm holding between 0.01 and 0.1 elements (dropper)

per m^2. A key finding relating to plant survival is the importance of wave–current interaction and co-effect (Seymour, 1996; Seymour et al., 1989; Elwany et al., 1995) whereby the role of currents that were in the direction of the waves were crucial to survival. In addition the identification of flow reduction within kelp beds (Jackson and Winant, 1983; Rosman et al., 2007) is fundamental for many aspects of shellfish farm design. Stratification is an issue in shellfish canopies (Plew et al., 2006) as it may serve to separate the crop from nutrient-rich waters or confine contaminant-laden waters with in the canopy. Jackson (1984) showed how internal wave variations would diffuse into a kelp canopy generating unpredictable phase differences between outside and inside flow variations.

Emergent vegetation canopies (i.e. reed beds) have some parallels to a large dense shellfish farm. Nepf and Koch (1999) showed how secondary recirculation would transport a tracer vertically with speeds reaching 15% of the background flow. This requires the dropper to penetrate well into the benthic boundary-layer. This may have implications for nutrient transport at the dropper scale and smaller. There are also similar issues relating to relative motion (Stevens et al., 2001) and with-in structure interaction (Stevens et al., 2004). These factors will influence the transport of nutrients within the canopy.

Floating breakwaters have been successfully deployed in a number of situations. They consist of moored dissipation elements, often a sequence of buoys or interlocking plastic shapes. Seymour and Hanes (1979) measured an array of buoys that reduced the wave energy flux by a factor of five in certain frequency ranges. The breakwater configuration is very much like a shellfish longline except that the longitudinal connection occurs at the ballast rather than between the floats.

An extension of the floating breakwater concept is a wave-energy converter that, instead of dissipating energy, transforms it into electrical energy via a variety of generator methods (e.g. Pelamis; http://www.oceanpd.com). These devices are of relevance to offshore shellfish engineering because their need to generate as much electricity as possible means they are designed to survive in very exposed seas. Furthermore, these devices provide some guide for mooring design (Ivanova et al., 2005; Vijayakrishna Rapaka et al., 2004). Development is very much focussed on individual devices and little work has been conducted on the effect of arrays of devices (Stevens et al., 2007b).

4. Effect of the flow on the farm: structural mechanics and forcing

4.1. Mechanics

The interaction between farms and hydrodynamics is important from the perspective of structural survival and wave attenuation. Large shellfish suspended culture installations affect currents and waves (Plew et al., 2005, in preparation). This is effectively a transfer of energy from the flow to the farm structure. There are two hydrodynamic drivers—currents and waves (Fig. 2). Currents can be considered to be steady in that their variability is generally slow enough that any structure responds comparatively rapidly. Hence, tidally driven currents which although they oscillate can be considered ‘‘steady’’ from the perspective of forcing.

Steady drag forces on a structure can be expressed in terms of a quadratic drag relationship based on fluid density ρ, a measure of area A, steady drag coefficient C_d and mean velocity U,

$$F = \frac{1}{2} C_\mathrm{d} \rho A U^2 \tag{1}$$

The choice of area is somewhat arbitrary provided that the drag coefficient is defined in a consistent manner, but projected area normal to the flow is commonly used. It is seldom that drag coefficients of an entire aquaculture structure are known and a first-order approach in estimating total drag is to sum the drag on individual components of the structure. It should be noted that considerable sheltering and interaction may occur between different components that will alter drag. The changes in drag depend on many factors such as spacing and orientation of the various components. In

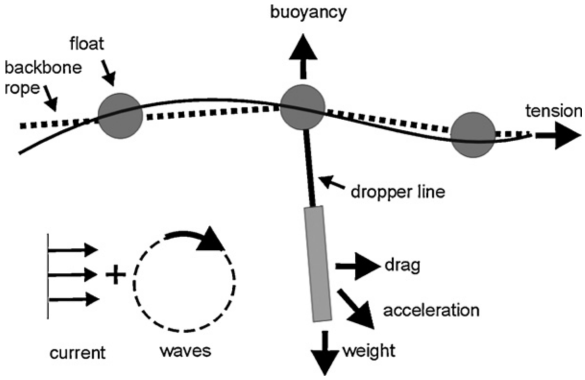

Fig. 2. Free body diagram of structural elements representing the connected floats and the mussel-laden stock loop. The driving hydrodynamics is contained in the waves and currents. The diagram shows representations of the forces controlling the motion.

particular, structures aligned with the flow will experience lower drag as downstream elements are contained within the wake produced by those upstream. For example, data for in-line arrays of circular cylinders show decreasing drag as cylinder spacing is decreased, whilst drag for arrays of cylinders angled to the flow is a function of array orientation and spacing (Plew, 2005). Alternatively, the entire structure may be regarded as a porous obstacle and planar aquaculture structures such as shellfish longlines resemble fences. Common design procedure for porous fences is to modify the drag coefficient by the sine of the angle of the fence to the flow (Cook, 1985).

Wave forces on a stationary submerged object consist of both drag and inertial components and are commonly described using the Morison equation (Morison et al., 1950),

$$\begin{aligned} F &= F_\mathrm{d} + F_\mathrm{a} \\ &= \frac{1}{2} C_\mathrm{d} \rho A u^2 + C_\mathrm{m} \rho V \frac{\partial u}{\partial t} \end{aligned} \tag{2}$$

The drag component F_d is parameterised as a quadratic function of instantaneous velocity u using a drag coefficient C_d and projected area A normal to the wave crest. The inertial component F_a represents the additional force required to accelerate the fluid around the object and is a function of fluid acceleration, displaced volume (V) and an added mass coefficient (C_m).

The total force on the structure is the combination of wave forces acting on the submerged crop, buoyancy and moorings (e.g. Falnes, 2002). The crop constitutes the greatest part of the structure in terms of surface area and wet mass and therefore sustains most of the loading. The total force acting along mooring lines will depend on the configuration of the structure. However, forces on individual components may be estimated using the Morison Eq. (2) with appropriate coefficients. The suspended shellfish crop resembles rough cylinders, therefore volume and projected area of crop rope may be parameterised using the width or diameter (d_r) and length (L_d).

Calculated wave forces are sensitive to the coefficients for drag and added mass C_d and C_m. These coefficients have been found to vary significantly with Keulegan–Carpenter number $K = (u_\mathrm{m}/Td_\mathrm{r})$ where u_m is the maximum horizontal water particle velocity in a wave cycle and T the wave period. Consequently, values of drag coefficients for steady flow are not appropriate for use in wave force calculations (Nath, 1987; Wolfram and Naghipour, 1999; Zdravkovich, 2003; Sarpkaya, 1987, 1990). In the absence of experimentally derived values, values of these coefficients for shellfish culture ropes may be estimated from data on roughened piles as the culture-encrusted crop ropes resemble heavily fouled cylindrical piles. Values of $C_\mathrm{d} = 1.7$ and $C_\mathrm{m} = 2.0$ are suggested for heavily roughened piles in the absence of a current (Wolfram and Naghipour, 1999). The effect of a current is to reduce both coefficients giving smaller wave induced forces.

In reality, suspended shellfish culture structures are flexible and move in response to the waves and the actual force is determined by the relative velocity between structure and fluid. There are likely to be both structural and hydrodynamic interactions between various elements of the structure which will modify response. Furthermore, there are additional inertial forces associated with the acceleration of the moving structure. However, a first approximation of the size of wave forces may be made assuming that motion of the structure is small relative to wave orbital motions (Fig. 2).

Swell waves will typically have wavelengths of the order of 150 m. Wave influence penetrates to around half the wavelength so that as this wave approaches shore it will start to change and lose energy once it reaches the 75 m depth contours. Considering deep water (where λ is less than twice the depth) conditions, the horizontal (u) and vertical (w) velocity components of the wave orbits are:

$$u = a\omega\, \mathrm{e}^{kz} \sin\varphi \quad \text{and} \quad w = a\omega\, \mathrm{e}^{kz} \cos\varphi, \tag{3}$$

where a is wave amplitude (half wave peak to trough vertical distance), ω is wave frequency in rad s^{-1}, k is the wavenumber = $2\pi/\lambda$ and $\varphi = (kx - \omega t)$. The deep-water phase velocity, the speed at which individual crests move, is

$$c_\mathrm{p} = \frac{g}{\omega}. \tag{4}$$

The horizontal particle displacement is

$$\xi = a\, \mathrm{e}^{kz} \cos\varphi. \tag{5}$$

Of course ocean wave conditions rarely consist of a single wave component (i.e. the wave field is not monochromatic). Instead a spectrum of waves exists (Fig. 3) resulting in a temporally complex forcing. So not only will there be a range of waves acting but there will be temporal variability in that waves are typically found in groups so that there will be periods of intense wave activity (Smith et al., 1996). Indeed it is likely that there is a non-linear aspect to this whereby the groups enhance periods of wave breaking. This in turn is likely to influence forcing of the longline.

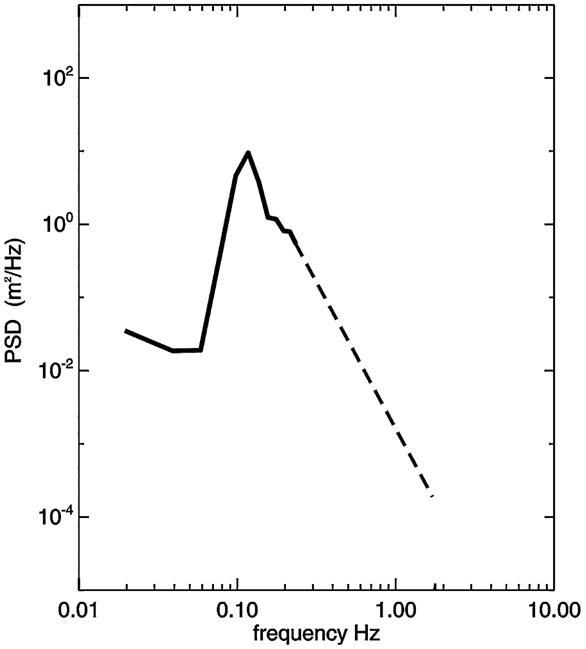

Fig. 3. A wave energy spectrum recorded with a bed-mounted pressure sensor. The dashed line shows an extrapolated spectral tail where bed-mounted sensors are unable to resolve surface wave data.

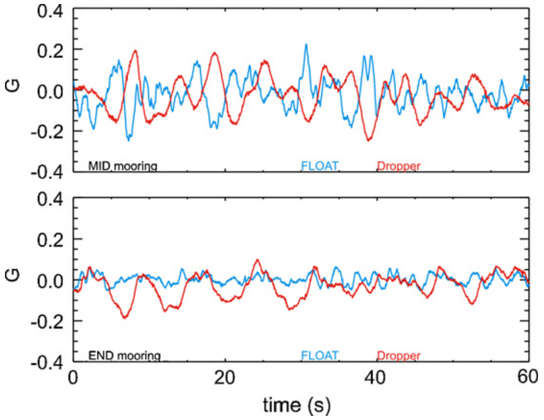

Fig. 4. Acceleration as a proxy for motion showing (upper) mid-longline and (lower) longline end response. The results are from data recorded on a longline in Pigeon Bay on Banks Peninsula near Christchurch, New Zealand (Stevens et al., 2007a).

This highlights the differences in field observational (full scale), numerical (computer) and laboratory approaches. Field observations are useful for identifying ranges of behaviour and certainly good for discovering unexpected modes of behaviour. However it becomes very expensive to sample sufficiently to determine all aspects of a problem. It is much easier to control parameters in laboratory and numerical experiments. Of course these are subject to scale (laboratory) and parameterisation (numerics) effects. Taking the example of a continuous wave spectrum this should be observable with adequate instrumentation. It can also be represented with sophisticated wave tanks. However, in many laboratory studies it will be useful to initially work with monochromatic wave.

When considering the dynamic outlay of shellfish structures it becomes clear that the biggest mass in the structure is the shellfish lines themselves. These elements are not well restrained, effectively being connected to the structure near the surface with a freely rotating pin and only confined by their weight and drag. Recent field (full scale) experiments that examined the various accelerations (Fig. 4) and force components due to waves and currents (Stevens et al., 2007a) recorded data in Pigeon Bay on Banks Peninsula near Christchurch, New Zealand. Pigeon Bay is around 1200 m wide, 6 km long and is flat-bottomed, gradually shoaling from around 15 m at its entrance. Two mussel farms run along the North West side of the bay, each containing 3 blocks with 6–7 backbones each. Fully stocked, this comprises around 80 km of mussel line. The total length of the combined farmed area is around 1 km and the blocks extend from within 30 m of the shore to a distance of 150 m offshore. Within the farms the water depth is around 12 m. In this inshore location the mooring tension due to the rise and fall of the tide is of a significant magnitude when compared to the other components. The farm under examination in Fig. 4 had average backbone tension forces of around 7 kN. Assuming the farm is a simple array of cylinders in a steady flow of 0.1 m s^{-1}, and summing the individual drag forces suggests a total tide-induced load of around 1.2 kN. This estimate increases if oscillating wave forces are included (Morison et al., 1950). The accelerometer data (Fig. 4) illustrate the variable nature of motion in different parts of the structure. The experiments also suggest that there may be substantial vertical motion and so vertical components of this force balance need to be considered also. Such full-scale measurements are very useful but often only for a focused period. An opportunity exists to interact with mussel industry groups to resolve data regarding how longlines fail or are damaged.

4.2. *Current measurement*

There are a wide variety of instruments available for measuring water current speeds. The type of instrument chosen for an application may be decided by cost, availability, ease of mooring and data requirements. In broad terms, instruments for measuring currents may be separated into two categories: point meters and profilers. Point meters provide velocity at a single position and methods of measuring water speed include impellers, magnetic induction and acoustic Doppler frequency shift. Impellers are easily fouled in a marine environment and modern instruments use magnetic or acoustic methods combined with an internal compass allowing direction to also be recorded. Several point meters may be moored at different depths to obtain a vertical profile of water velocity.

As the offshore oil industry discovered (Bole et al., 1994), internal wave processes drive vertically varying flows within the water column which may result in high transient structural loading. These internal waves are quite common in certain locations and conditions (e.g. Colosi et al., 2001; Stevens et al., 2005). The interaction of the tide-driven stratified water column with the sloping bed generates large relatively slow-moving oscillations of the isotherms within the water column. These waves steepen naturally and can result in some rapid velocity fluctuations. They tend to be well dissipated by the time they reach shallow inshore waters but structures in 50 m or more of water may experience substantial flow variability. Hence there is a need to measure flow throughout the water column.

A tool that makes this possible is the Acoustic Doppler current profiler (ADCP). As the name suggests, these devices measure water velocities at several depths by measuring the Doppler shift in an acoustic pulse reflected by natural suspended material in the water column. These instruments are able to record horizontal and vertical velocity components in a number of cells spaced at increasing distances from the instrument. The distance range of the instrument depends on water quality and on the frequency of the transmitted acoustic signal with shorter ranges but finer resolution obtained by higher transmission frequencies. These instruments are commonly deployed on the bed, but may also be moored partway up the water column or attached to a moving vessel to provide a spatial survey of flow (Munchow et al., 1995). It is perhaps most useful to combine approaches so that the timeseries mooring provide a reference for survey work.

4.3. Wave measurement techniques

Although waves are visually readily observable they prove to be quite difficult to measure reliably. Tucker and Pitt (2001) provide an excellent introduction to the topic. A time-series of water elevation measured at any point will typically contain an irregular waveform. This can be represented with a combination of waveforms with differing periods, height and direction. Hence it is common to describe waves with statistical parameters. The more important of these, in terms of design, are significant wave height H_s and the period of the waves containing the most energy T_p. Historically, H_s has been described by the average peak to peak amplitude of the largest one third of waves. With continuous digital measurement now very common it is usual to describe H_s as four times the standard deviation of elevation. Other descriptors include wave energy spectra and direction spectra, which show the distribution of energy and wave direction as a function of wave period. Wave characteristics are obtained by measuring some aspect related to the oscillatory motion of the waves such as changes in water level, pressure, velocity or acceleration.

The most direct method of measuring wave height and period is to record the changes in water level as waves pass over an instrument. Examples of water level recorders include capacitance wave gauges, echo sounders and laser altimeters. A less direct but widely used method is to record the hydrostatic pressure changes beneath waves. Pressure recorders are relatively cheap, robust and reliable, however they do have limitations. Pressure recorders are not able to provide wave direction, must be motionless to obtain accurate pressure measurement (such as bed deployment or rigid mooring), and are limited by frequency dependent attenuation of pressure fluctuation with depth (Jones and Monismith, 2007). High frequency waves are attenuated more rapidly with depth, and the shortest waves that can be detected are those with wavelengths greater than twice the instrument depth (Tucker and Pitt, 2001). Wave direction can be inferred by using spatial arrays of pressure sensors that log simultaneously, although it is more common to use a combination of pressure and velocity. Pressure sensors will be difficult to use in any but the shallowest of shellfish applications.

Wave height and period can also be inferred from orbital velocities. Both point current meters and profilers can be used to measure the velocities. These orbital velocities require a correction if there is a mean current present. The same frequency-dependent attenuation with depth described for pressure sensors limits the frequency range of bed-mounted velocity sensors. However ADCP's can resolve orbital velocities higher in the water column so that a number of techniques have been developed to obtain directional wave properties (e.g. Visbeck and Fischer, 1995): Many are equipped with pressure sensors and by combining velocity measurements with pressure fluctuations, wave height, period and direction may be derived.

Direct measurements of surface height can also be obtained by using the acoustic beams as a form of echo sounder. If high sampling frequencies are used, then orbital velocities can be measured at different depths and extrapolated to the surface. This method allows higher frequency waves to be detected in comparison to a pressure sensor moored at the same depth. An important advantage of using acoustic Doppler profilers is that current measurements can be obtained at the same time. Surface buoys fitted with accelerometers (often called ‘‘waveriders’’, although this is a trade name) are now the most common way to operationally provide measured wave heights and periods. Vertical accelerations are integrated twice to obtain displacements (wave heights). Moderately high frequency waves can be detected without requiring any correction for depth attenuation. Typically, these devices are combined with telemetry to provide near real-time data.

4.4. Farm motion measurements

Failure of shellfish grow-out mooring components can occur if excessive movements exist. Cyclical loading, primarily due to surface waves, can wear connections, cause abrasion in rope and in extreme situations, snap buoys resulting in complete failure. Understanding the motion response of critical components, especially in an irregular sea, is important to prevent such failures. Measuring the in situ response can be achieved using accelerometers (Fig. 5). Relatively inexpensive tri-axial accelerometers sense three degrees of freedom (DOF), whilst ‘‘motion sensing’’ packages will resolve six DOF (heave, surge and sway, as well as rotational components—pitch, roll and yaw). The accelerometer measurements are digitised and numerically integrated to obtain velocities and displacements. Examining the time series under various wave and current forcing conditions can identify movements due to ‘‘snap’’ loads that can lead to component failure. It is likely that such timeseries will need to be sufficiently long to capture extreme events as the data in Stevens et al. (2007a) did not identify any extreme response modes. The accelerometer data can also be integrated and examined in the frequency domain and transfer functions calculated using the techniques described by Fredriksson et al. (2005). Transfer functions provide a normalised response to irregular waves in a wind wave and/or swell sea so resonant motion conditions can be identified.

Measurements of mooring system tensions require high capacity load cells that use strain gauge technology (Window and Holister, 1989). Load cells are typically installed in line with mooring components. Changes in voltage detected by the strain gage components are conditioned, amplified and sent to a data recorder. Fig. 6 shows a load cell connected to a mooring chain with an inline ‘‘strong back’’.

The motion sensing and load cell packages deployed in situ require a power supply, analog/digital conversion, data storage and software to control the system. Often it is useful to record synchronised loads and accelerations (say to within 0.01 s) from various locations around a structure. At present this can only be achieved by running cables around the structure. Irish et al. (2001) provides the details on the construction of a motion package system used specifically for a marine aquaculture application. If the information is to be acquired remotely, a telemetry

Fig. 5. Accelerometers mounted on (a) surface float (the accelerometer is inside the silver container) and (b) a ‘‘dropper’’ where the data is carried up the cable to the logger shown in (a).

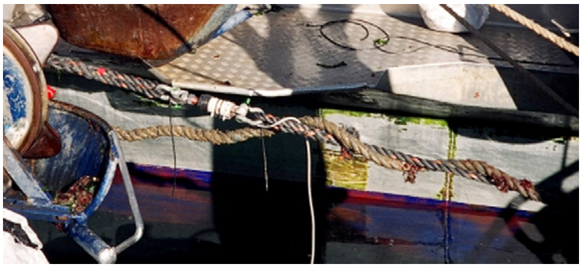

Fig. 6. Load cell mounted inline on a mussel anchor rope.

system can also be included in the hardware package. Other instrumentation systems used to measure motions are also commonly found on oceanographic buoys to infer surface wave elevation (for example, see Steele et al., 1985).

4.5. Remote sensing

A novel way to simultaneously measure farm motion, waves and currents is provided by radar technology (Stevens et al., 2007b) although this will only work in specific circumstances. However, larger-scale radar using HF or VHF are perfectly sized to quantify the influence of farms on currents and waves (Heron and Prytz, 2002). This is important because a major unknown in the development of large-scale farms is the consistent effect on regional current patterns. The natural variability inherent in coastal flows makes it difficult to determine this from a few ADCP surveys or a current meter mooring. Instead a HF radar installation over a period of a few months before and after farm installation should provide a clear picture of flow distributions and the impact of the farm.

4.6. Farm motion modelling

The modeling of shellfish growout systems typically employs the Morison equation technique (2) so that drag and inertia forces are calculated on each element (Raman-Nair and Colbourne, 2003). The approach is suitable for aquaculture structures because most of the components have small diameters with respect to the forcing wavelength and therefore diffraction effects can be neglected. The model AquaFE which has a history of examining finfish growout systems and has also been applied to shellfish systems to synthesises these processes. The model is most recently described in Tsukrov et al. (2003, 2005) and DeCew et al. (2005) and uses a Morison equation approach with finite elements (see Section 4.1 above). It represents the structure with a series of elements and drives them with parameterised loads based on the local hydrodynamics. It does not feedback and influence the flow. Stresses and motions of shellfish farm components have been calculated using the model. An example of one application is shown in Figs. 7 and 8. In the model, a mussel farm with a backbone length of 120 m suspended with mussel with looped droppers with a length of 16 m. The results showed high frequency swaying of the dropper loops suggesting that the flexibility of the dropper lines needs to be accurately assessed. An issue when using AquaFE for shellfish farm structures is the method the model uses to calculate drag coefficients. These coefficients are calculated as a function of Reynolds number using an empirical approach described in Choo and Casarella (1971) developed for smooth cylinders. Work is required to identify sets of drag coefficients for other components and then incorporate these factors into the model (Plew, 2005).

4.7. Mooring design

Moorings in inshore shellfish developments are typically simple concrete ballast blocks. However, this is likely insufficient in offshore applications. Instead either locked screw-anchors or more traditional anchoring systems are used (Fig. 9). Paul and Grosenbaugh (2000) describe moorings using ~2000 kg anchors and lines formed by a combination of chain and polyester rope. Such developments are difficult to predict as some degree of trial and error is required. Furthermore, the installation depends on the substrate. Options include sharing of mooring points between longlines and ways of reducing transient loads. Float designs that spread such transient loads in time are likely to prove beneficial. This can be achieved by using long "spar floats" so that the change in buoyancy force with vertical submergence is not high. An alternate approach might be to combine the mooring arrangement with offshore wind turbine installations (Buck, 2007).

5. Flow-related environmental issues and associated technology

To date much of the emphasis on the study of environmental impacts of shellfish farms has been associated with benthic deposition (Dahlback and Gunnarsson, 1981; Mattson and Linden, 1983; Giles and Pilditch, 2004) and nutrient depletion. However, far-reaching effects may also be associated with wave attenuation, current distortion and disruption of stratification (Plew et al., 2005, 2006; Boyd and Heasman, 1998; Strohmeier et al., 2005; Grant and

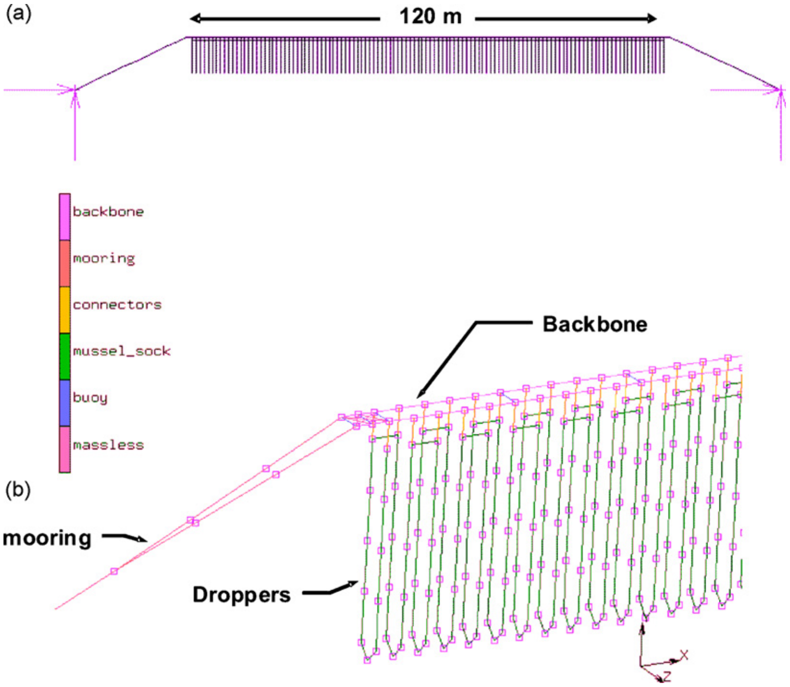

Fig. 7. Model arrangements showing (a) a side view of a surface mussel farm system with large number of droppers suspended from backbone line. The anchors are modeled as fixed points. (b) A close-up of the surface mussel farm structure showing the backbone, mooring and looped dropper components.

Bacher, 2001; Grant et al., in press). Likely stocking densities suggest there will be little wave attenuation at swell wave frequencies but that surface floating farms will strongly attenuate shorter wind-waves. However this reduction is reduced if the farm is submerged.

Water flow rates around a shellfish line is an important variable for estimating nutrient depletion (Ackerman and Nishizaki, 2004). Consequently, the initial challenge is to adequately understand local flow and flow-variability. Flows near the coast are essentially in a coastal boundary layer and can be subject to substantial flow-variability. Currents are significantly affected by farms structures to the extent that within farm flows might be as little 25% of the outside flow (Fig. 10). Understanding this slow-down within the farm is critical for understanding spatial growth variability in the farm and also likely levels of nutrient depletion. The impact of this flow reduction is compounded by the tidal excursion envelope (i.e. how far a particle is advected in one phase of the tidal cycle) and the strength of tidal current amplitude relative to unidirectional flow. Furthermore, the spatial distribution of changes in flow is not simple as there are areas where the disturbed flow actually speeds up, around the corners of a farm for example.

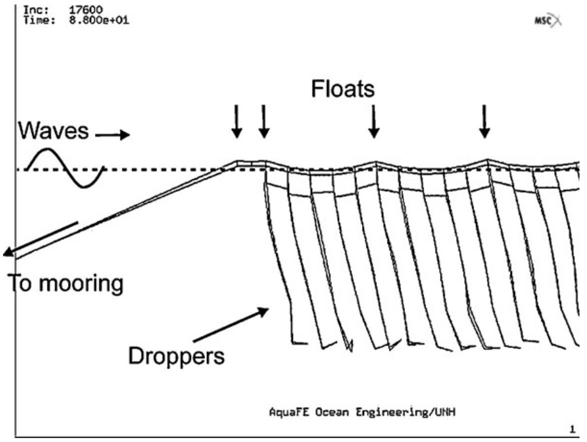

Fig. 8. Snapshot of a section of a finite element model of a longline being forced by surface waves. The arrows identify the location of float elements in the model.

At a fundamental level benthic distributions of material are a combination of understanding the mean and variability of currents and turbulence and the injected material, its sinking rate and adherence to the bed. Hartstein and Stevens (2005) developed a mussel farm biodeposits (faeces and pseudofaeces) index of dispersal that that illustrated the importance of knowing local current variability and the sinking speed of the biodeposits. Technology for observationally evaluating

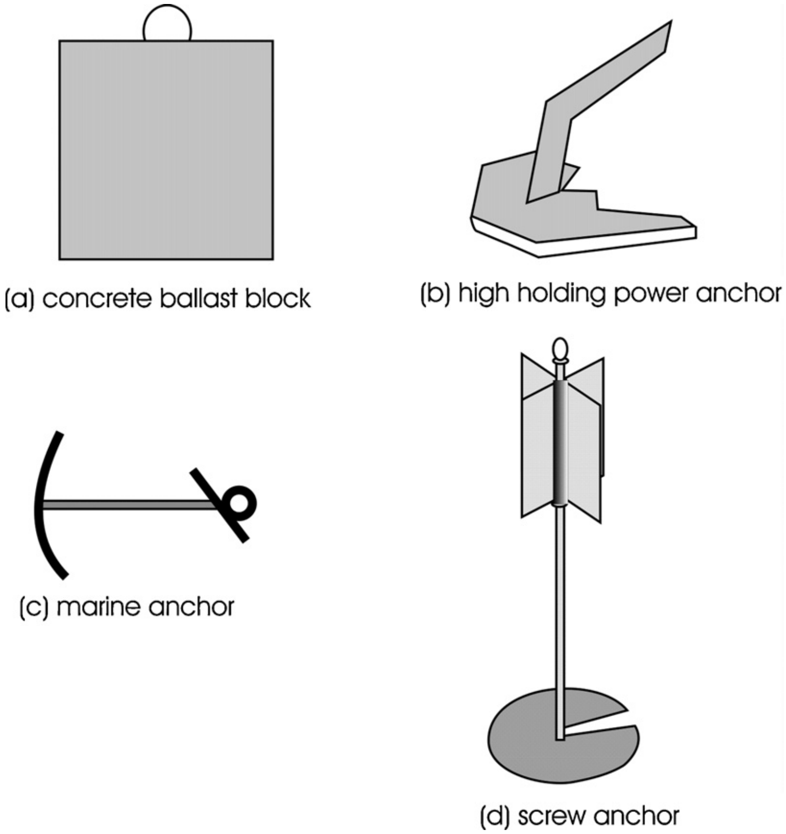
(a) concrete ballast block
(b) high holding power anchor
(c) marine anchor
(d) screw anchor

Fig. 9. Examples of anchoring.

deposition distribution and benthic type is advancing through the development of acoustic seabed mapping using either side scan sonar, multi-beam or single beach eco-sounders (Fig. 11).

Numerous studies have previously used acoustic sonaragraphs to characterise sediment textures of many seabed types ranging from deep seafloor (Damuth, 1975) to inner shelf sediment (e.g. Davis et al., 1996; Ward and Birch, 1999). This technology is now being used to examine the spread of aquaculture debris (biodeposits and shell accumulation) around mussel and finfish farm sites (Tlusty et al., 2000; Hartstein, 2005).

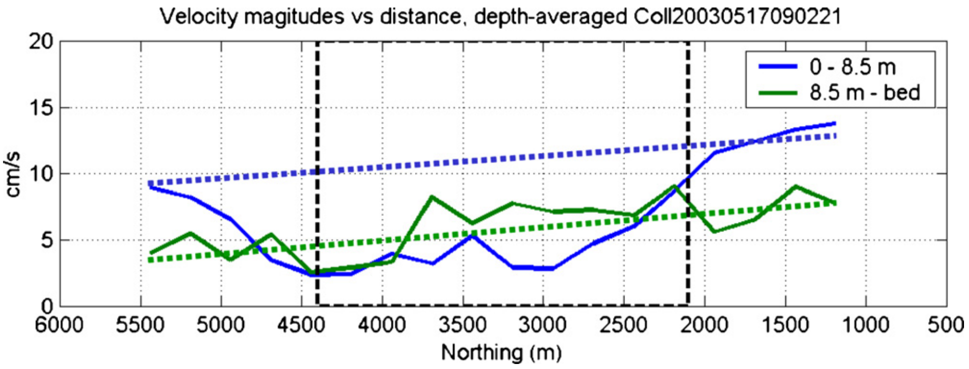

Fig. 10. Observation reduction in flow speed during an ADCP transect through a farm. The data come from the experiment described in Plew et al. (2006, in preparation) on a farm situated approximately 2.5 km offshore and has dimensions of 2450 m × 650 m in plan with the long axis parallel to the coast. The farm consists of approximately 220 longlines with a dropper density 0.06 droppers m^{-2}. The vertical dashed lines represent the extent of the farm.

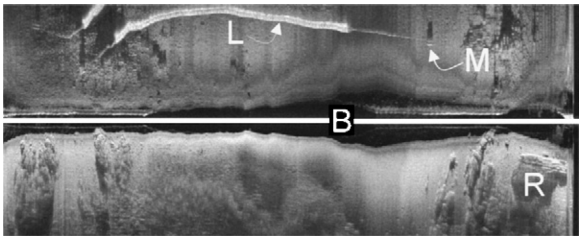

Fig. 11. Sidescan image courtesy Ken Grange (NIWA, NZ) showing a longline (L), mooring (M), reef areas (R) and blanking beneath sidescan (B).

Hartstein (2005) used side scan sonar to map mussel farm debris at both open-ocean and sheltered inner shore sites and found clear distinction between mussel farm debris and natural seabed sediments in and around the farm sites. In other words the benthic footprint of the farm was identifiable in these particular situations. Tlusty et al. (2000) found that a combination of side-scan sonar and multi-beam surveys could be used to identify organic enrichment and/or shell drop on the seabed beneath fish and mussel farm sites in Newfoundland Canada. These surveys were also used to aid in the site selection process. Areas of rocky reef and mud were distinguishable and the seabed was subsequently mapped and rocky reef areas excluded from aquaculture management areas on the assumption that they will be unduly affected by deposition. As a result of this study, acoustic seabed identification is now a regularly monitoring and site selection tool used, for example, by the Department of Fisheries and Oceans Canada (Hartstein et al., in press). In addition rather than using expensive side-scan sonar and multi-beam devices Hartstein et al. (in press) examined a number of farm sites in Atlantic Canada using cheaper single beam eco-sounder. In this study the farm footprint was identifiable and the approach is now being considered as an additional farm site-monitoring tool. It must be noted that, as with all acoustical data, visual verification is required, usually by sample collecting (i.e. seabed sediment) or towed cameras, etc. Such ground-truthing is typically conducted on a small diagnostic data set, and once established for an area can be used to geologically/biologically interpret a larger study area.

Recent developments on satellite-based remote sensing means that open-water aquaculture facilities can be seen from space. As well as engineering-relevant quantities like currents and wave, remote sensing can provide proxies for biogeochemical quantise. Instruments like MODIS provide ocean colour that enable background chlorophyll distributions to be gauged, within the limits set by algorithmic abilities to separate oceanic water from sediment-laden river plumes (Maritorena et al., 2002).

One of the more emotive and less-quantified aspects of large offshore installations is their likely effect on marine mammals especially as a hazard for migrating whales. This topic is often reviewed for environmental impact assessments for coastal developments. However, there is little hard evidence upon which conclusions are drawn. The growing offshore wind energy sector in Europe is starting to consider the effects of these distributed structures (Köller et al., 2006; Tougaard et al., 2003). There are synergies with seabird issues also (Roycroft et al., 2004). Development of offshore shellfish farms is an opportunity to address this deficit through various monitoring techniques.

6. Synthesis

Understanding the mechanics of such structures is vital for correct prediction of response in extreme conditions as well as for avoiding over-engineering in design. Additionally, this is a highly interdisciplinary topic and the engineering cannot be entirely separated from the biology. It is clear that understanding the interrelation between a shellfish farm and the surrounding flow is multi-scale (Fig. 12). Feeding and spat retention all takes place at the cm scale, much of the dynamics forcing takes place at the line/wave scale yet nutrient depletion/recovery has embayment/coastal boundary-layer scales. There are two facets to this. First, experiments must be designed to capture a sufficient range of energetics at the important scales. Sampling these multiple scales requires a multi-faceted approach (Fig. 13). It is not necessary to carry out measurement at all scales for all periods. Large-scale variations will require the longest sampling periods whilst variability in the small-scale processes might be captured with a few tidal cycles. The second facet is that understanding must incorporate these scales. For example, flow right next to a mussel that influences filtration will need to be based on measurements at that location as flow speed and direction are likely very different to some background average flow rate. We believe that we are in the early stages of developing an understanding of the coastal environment that is sufficient to enable a sustainable offshore industry to develop and flourish.

6.1. Future research emphases

Naturally there will be regional foci depending on local farming style, experimental conditions and

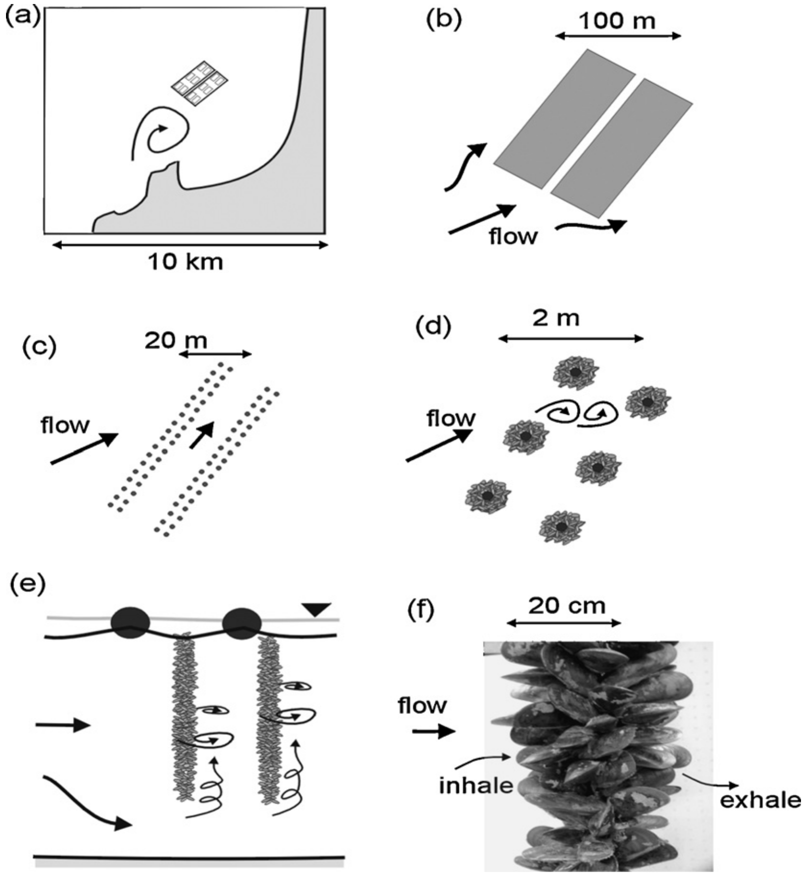

Fig. 12. Multiple scales of flow relevant to shellfish farms showing (a) coastal flow variability, (b) farm flow distortion, (c) longline scale with flow variability in between lines, (d) dropper scale with wake interaction, (e) vertical dropper scale with under farm acceleration and recirculation and (f) mussel scale with redistribution of in and exhale flows.

legislative emphasis. We suggest future research challenges will include, but not be limited to, the following topics.

- Vertical/angular drag and added mass coefficients. Much of the flow, especially due to waves is not perpendicular to the axis of the shellfish droppers. Instead, study of the basic hydrodynamics of these ‘‘very rough cylinders’’ needs to explore the energy and mass transfer (i.e. mussel feeding) as the elements move up and down in the water column.

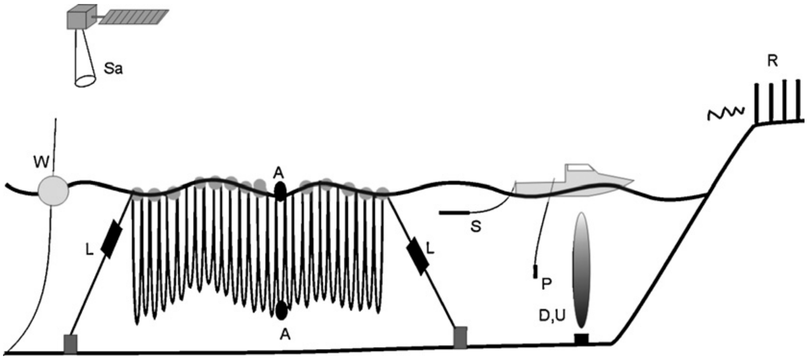

Fig. 13. Sampling technology diagram showing structural monitoring (loads L, acceleration A), driver monitoring (wave rider W, currents U, depth D), environmental conditions (side-scan benthic S, water column profiling P), and remote sensing approaches including satellite (e.g. ocean colour MODIS, Sa) and land based (e.g. HF radar for waves and currents R).

- Understanding water column processes including stratification of density and nutrients, under farm acceleration, resuspension of detritus and internal waves.
- Research into structural outlay that takes best advantage of flow to maximise nutrient uptake (e.g. Smith et al., 2006) needs to be extended to incorporate feasible harvesting methodology.
- Dynamic mooring design needs to incorporate the likely effect of wave–current interaction so that ‘‘line-snapping’’ can be avoided without requiring large pretension loads. Development of smarter float design, a spar float or modified center of buoyancy float are possible methodologies.
- Wave forcing and the effectiveness of submergence on reducing wave effects, ‘‘non-linear’’ wave effects such as wave/current interaction wave and current co-directionality and the effect of wave groups on generating high loads.
- Effect on marine mammals and sea birds—developing a reliable database and experimental methodology may be one of the great challenges to getting legislative approval for offshore farm development.

Acknowledgements

The authors wish to thank Barb Hayden, Ken Grange, Jud DeCew, Gary Teear, Roger Nokes, John Zeldis and Bob Spigel for their assistance. Four Anonymous Reviewers also provided valuable comment on the paper. This work was primarily funded by the New Zealand Foundation for Research Science and Technology.

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