Correcting the Under-estimate of the Tidal-Stream Resource of the Pentland Firth

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Abstract

The equation used for predicting the output of a wind turbine in an open flow field uses the cube of wind velocity. But the correct equation for an hydraulic machine in a closed duct uses the first power of flow rate times the pressure head. This paper argues that the second equation should be used for close-packed tidal-stream turbines in long channels where the water has no easy escape path and that it will lead to a much larger estimate for the size of the resource. It seems wrong to base the design of tidal steam plant on a fundamental misunderstanding of the energy source.

Keywords: Pentland Firth, tidal-stream energy, bed friction, vertical-axis turbine, variable-pitch, flow impedance.

1. Flow fields

In the open flow field round the rotor of a wind turbine for which a greedy designer has used chords, rotations speeds or pitch angles greater than those suggested by the Betz momentum-change analysis, it is easy for the air to flow around or over the rotor rather than through it. We have the equivalent of what electrical engineers call a low impedance flow source. However for a high impedance flow in a channel with few escape paths the water *has* to flow through whatever obstructions are placed in its path and will raise enough head to do so. One of several obstructions is the friction of water flow at the sea bed.

The Proudman Oceanographic Laboratory [1] gives computer predictions for the surface velocity for the Pentland Firth and its approaches. Numbers are given at each of an array of rectangular cells measuring 1/40 degree by 1/60 degree. At the latitude of the Pentland Firth the area per cell is about 2.617 x 10^6 m^2.

If, for each cell, we multiply half the density of sea water by the cell area times the cube of the velocity at the spring peak and sum over all the cells, the result is 6.165 Terawatts with perhaps more from outside the area covered by Proudman.

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If we wish to estimate the power being lost as friction we would multiply this value by a friction coefficient. However we must make sure that we are not confused by the different definitions as used by engineers (who use 'half density' in their friction force equation) and oceanographers who leave out the half.

There are many friction values we could choose. For both sides of the very thin NACA 65-006 section, which is what one might choose for the fin of a guided missile, Abbot and von Doenhoff [2] give the drag coefficient of 0.0035 at zero angle of incidence. A great many other wing sections have values of 0.005. But figure 1 shows what the bed of the Pentland Firth is really like.

Figure 1. Growths of Laminaria Hyberborea, found in depths up to 30 metres in the Pentland Firth, are not similar to fighter wings.

Figure 2 shows photographs from the centre of the Pentland Firth where there is insufficient light for much plant growth. Again any resemblance to fighter wings is slight. Figure 3 shows a collection of friction coefficients for various situations. The highest values include the effects of waves but these are often present in the Pentland Firth.

So far there have been no measurements of the friction coefficient for the Pentland Firth but values have been measured by Campbell et al. [3] for the Menai Strait between Anglesey and the Welsh Mainland. The average of the February and November observations in the engineering convention is 0.017. When this coefficient is multiplied by 6.165 TW, we see that the Pentland Firth bed-friction loss at the peak of the spring tide would be 104.8 GW. However on the basis of photographic comparisons Bryden [4] estimates a friction coefficient of 0.04 (eight times more than a typical aircraft wing at zero incidence) leading to a *peak spring* bed loss of 246 GW. In addition to a rough bed the charts of the Pentland Firth show two major obstructions in the form of the islands of Swona and Stroma, gullies and shallows and a 30 degree bend at the exit into the North Sea.

If large amounts of energy are being dissipated as bed friction now, then the installation of the first tidal stream systems will have very little effect. If the installation of turbines were to reduce the velocity by say 20% there would be a 50% reduction in the energy of bed losses, much of which would be available to the turbines. MacKay [5] arrives at similar conclusion by treating the tidal movements as shallow water waves and calculating the energy per unit width. He also suggests another way of looking at the problem is to imagine that the Atlantic is the piston and cylinder of an enormous engine which is driving an enormous crankshaft in the North Sea through an enormous connecting rod in the form of the Pentland Firth. The official consultants can observe the connecting rod through ports in the crank case and measure its velocity. They know the density of the cast iron used to make all early connecting rods and so are able to calculate its kinetic energy. When somebody suggests that replacing the cast iron with titanium or carbon fibre they object that this will reduce the kinetic energy which is all that they have so far considered.

Lambeck [6] gives a range of estimates for mean world tidal dissipation. If we ignore ones from the 1920s the range is from 3.2 to 7.28 TW. Le Provost and Lyard [7] give a useful list of estimates of total *mean* world dissipation of tidal energy with ranges from, 2.46 TW up to 2.51 TW. They also say that 40% of this is dissipated in the North Atlantic.

It is important to ask where this is dissipated. For a given flow of water in a shallow water wave the velocities will be inversely proportional to the local depth. When we cube this reduction we can see that deep water in mid Atlantic will be dissipating very little. However, if the local velocity is not high enough to disturb ooze, then we can also expect lower friction coefficients giving a further reduction by perhaps an order of magnitude.

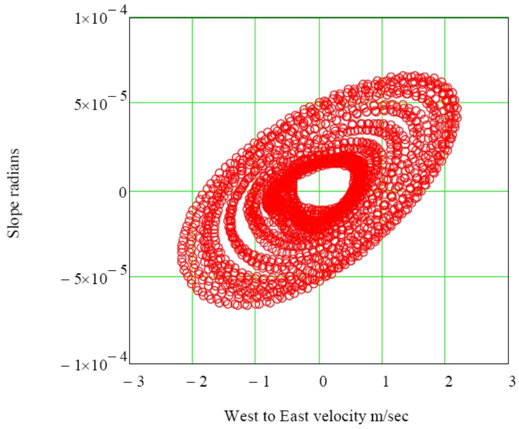

Figure 4. A Lissajous plot of slope against velocity.

Next we can argue that, if the tidal flow in a large ocean is blocked by some obstruction such as Portugal or Ireland, then it will generate the node of a standing wave with no horizontal component of velocity to dissipate energy at the sea bed. This suggests that by far the most dissipation will occur in shallow gaps between basins where there is a large phase difference of which the English Channel and the Pentland Firth are excellent examples. As global data are given as the mean, which might well be one sixth of the peak spring values, we can see that several approaches are reasonably consistent.

A further complication is that, if we plot the Proudman prediction for the slope along the Pentland Firth against the flow velocity at the centre, as in figure 4, we find that they are not in phase.

If we use zero crossings as a way to measure phase, we find that velocity lags slope by 63 degrees. If we use real and imaginary components of the M2 period of the two Fourier transforms, we get 58.1 degrees. Prandle [8] used the voltage induced in a cross-firth telephone cable by the action of the earth's magnetic field and found phase anomalies averaging 68 degrees.

This means that the channel has too much inertia to be in resonance with the main M2 driving period. We know from wave energy that changing the phase of a power take off force, known as reactive loading, allows resonant periods to be shifted. This could make the Pentland Firth attract more energy from the Atlantic.

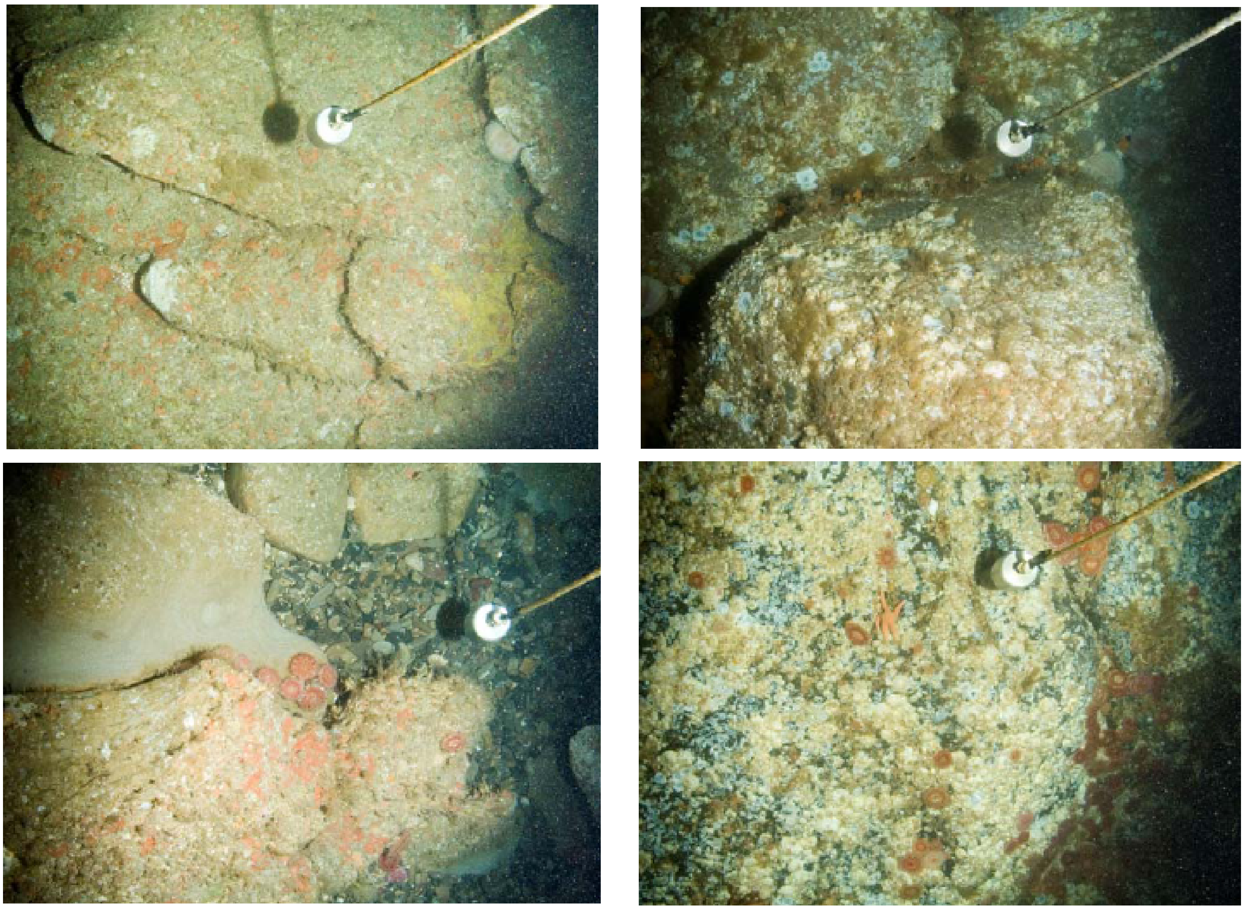

Figure 2. Images from the centre of the Firth shows the condition of the sea bed where light levels are insufficient for plant growth. The white marker is 60 mm in diameter. Courtesy Peter Hayes, Fisheries Research Aberdeen.

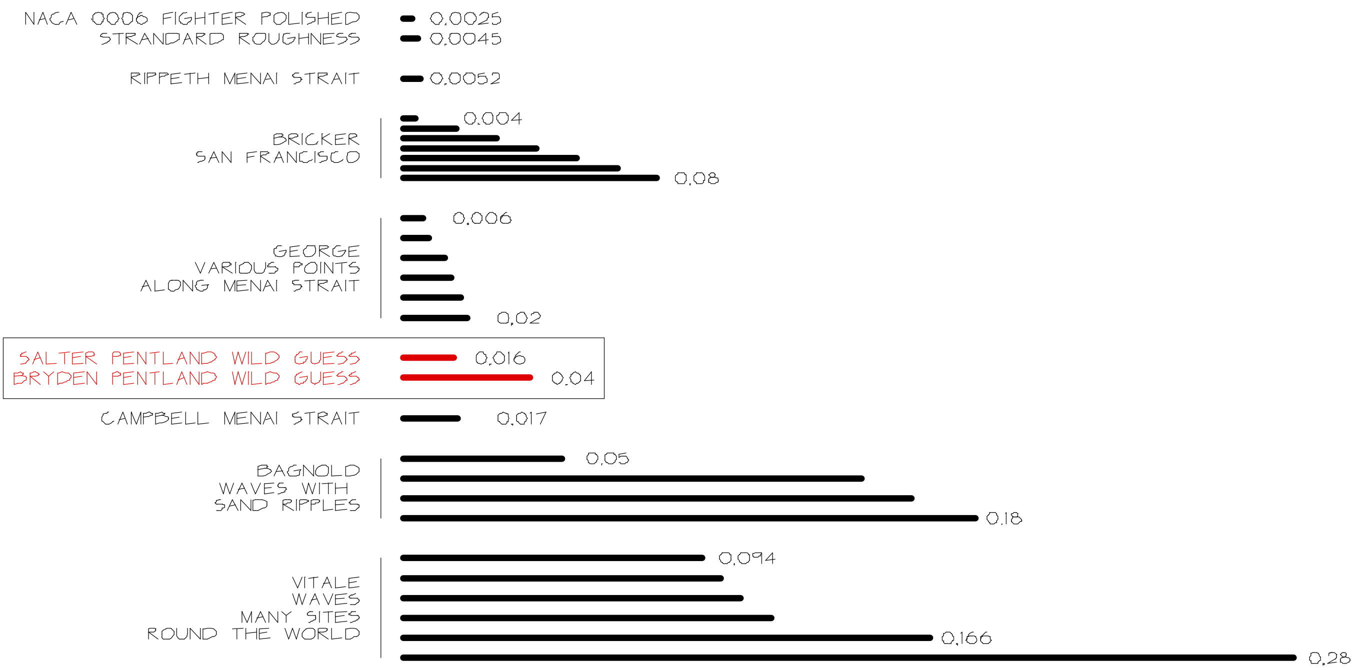

Figure 3. A collection of friction coefficients with bars drawn to scale using the engineering 'half density' convention.

2. Implications for design

Official estimates of the tidal stream resource continue the traditional practice of wind turbines and assume that they should be spaced three rotor diameters apart. This is like saying that the upper basins of conventional hydro-electric schemes should have leaking walls. It would lead to even more turbulent flows than at present. If we want lots of energy we should even grudge the difference between a square an a circle which is inevitable with horizontal axis machines and go for the rectangular flow window of vertical axis turbines packed as closely as possible and reaching from the surface as near to the sea bed as we dare. Given that much of the Pentland Firth has depths of 70 metres we can see that the bending moments at the root of any conventional tower will be large.

The first units will have to work in an open flow field and achieve the momentum change as dictated by Betz. But this requirement will be removed as they are joined by later ones. The tip speed ratios of all tidal stream plant are set by cavitation to much lower values than are desirable for wind. This needs an increase in solidity and increases the need for variable pitch in vertical axis units. This means that we should give initial turbines a high solidity but use low blade pitch angles and increase these angles later when the close-packed bank can develop a higher head than the Betz analysis would suggest.

A way to calculate the correct change of blade angle to present a chosen head distribution across a rotor through the rotation cycle is given in Salter and Taylor [9]. It involves dividing the flow window into a set of vertical strips of equal blade-transit time interval. The current speed and the rotation speed give the resultant flow velocity and direction in each slit. We wish for a particular downstream force in each slit but this can come only from the lift force on the blade which will be nearly perpendicular to the resultant velocity. We can therefore calculate the size of the lift force which will have the required downstream component. If we know the local flow velocity and the area of the blade we can calculate the angle of incidence to give this lift. The resulting angles are shown in figure 5.

The torque reaction from a horizontal axis machine will induce an opposite rotation in the cylinder of water in its wake and so produce a vortex. Because of cavitation problems the tip speed ratios of tidal stream plant have to be much lower than for wind turbines. If we have to reduce speed but not power we must increase torque and so rotational kinetic energy in the wake will be proportionally higher. But, in contrast, if we give vertical axis machines opposing directions of rotation we can cancel the torque reaction losses

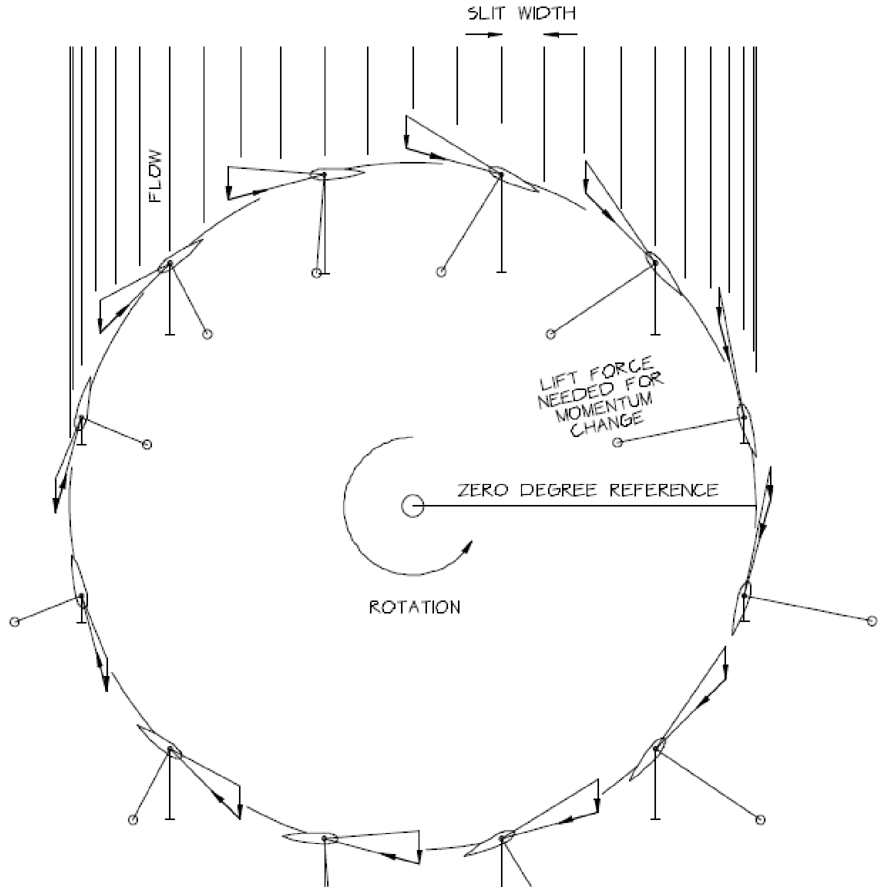

Figure 5. The pitch angles to give an even head across the flow window. Vectors with T-ends are the downstream forces for each slit. Vectors with circle ends are perpendicular to the resultant velocity vector.

3. Obstructions to navigation

The introduction of a large amount of tidal stream generation plant will undoubtedly affect the freedom of navigation in the Pentland Firth and the implications must be studied carefully. Nomadic tribes once felt it was their right to move herds anywhere that seasonal changes suited them. Later civilizations have used fences and traffic regulations to allow safety at very much higher traffic densities. The freedom of the air is even more strictly regulated. Following a series of dramatic oil spills and the potential for accidents with natural gas carriers, people are arguing for stricter policing of congested sea passages with better lane discipline and the prohibition of some cargoes.

The starting point of any plan for the Pentland Firth has to be easy access to the oil storage facilities on Flotta. Even if we have used more than half the North Sea reserves we have not yet passed half the cash value. We must also allow, as far as possible, local activities especially ferries and fishing.

Mariners accept that there are many hazards at sea and generally like to have them clearly marked. There seems to be no value in having 'moderate' obstruction. If we are to have any we should have all or none.

Figure 6 shows a plan intended to encourage discussion. It shows over 1200 close-packed, 140-metre diameter, 70 MW vertical-axis rotors placed in double rows. Units in either row can be removed and can move themselves or be towed along the 1500 metre gaps between rows. There is only 3 metres between units in the same row, the very minimum for the passage of an inflatable work boat. Removal of a rotor can benefit from active hydraulic spars between adjacent rotors which can also offer pedestrian and cycle traffic. The gap inside a double row is 15 metres to allow boats between rows to pass each other.

The narrowest gap for traffic in and out of Flotta is 2000 metres wide off Brough Ness. This should be compared with the 1100 metre width of the Forth at the entrance to Grangemouth, the 900 metre entrance to Milford Haven and the 800 metre gap at Fawley. Along both north and south coasts there is a minimum 400 metre gap to allow small vessels to make uninterrupted passages east and west. Large vessels can enter the Firth through a 1000 metre gap past two rows at Dunnet Head but they would then have to move across the firth to a 1000 metre gap at Brims Ness round the next pair of rows. This would add 7 nautical miles to their passage but would avoid the very fast currents round Tor Ness on Hoy. There is almost no impediment to traffic across the firth from Caithness to Hoy, Flotta and South Ronaldsay.

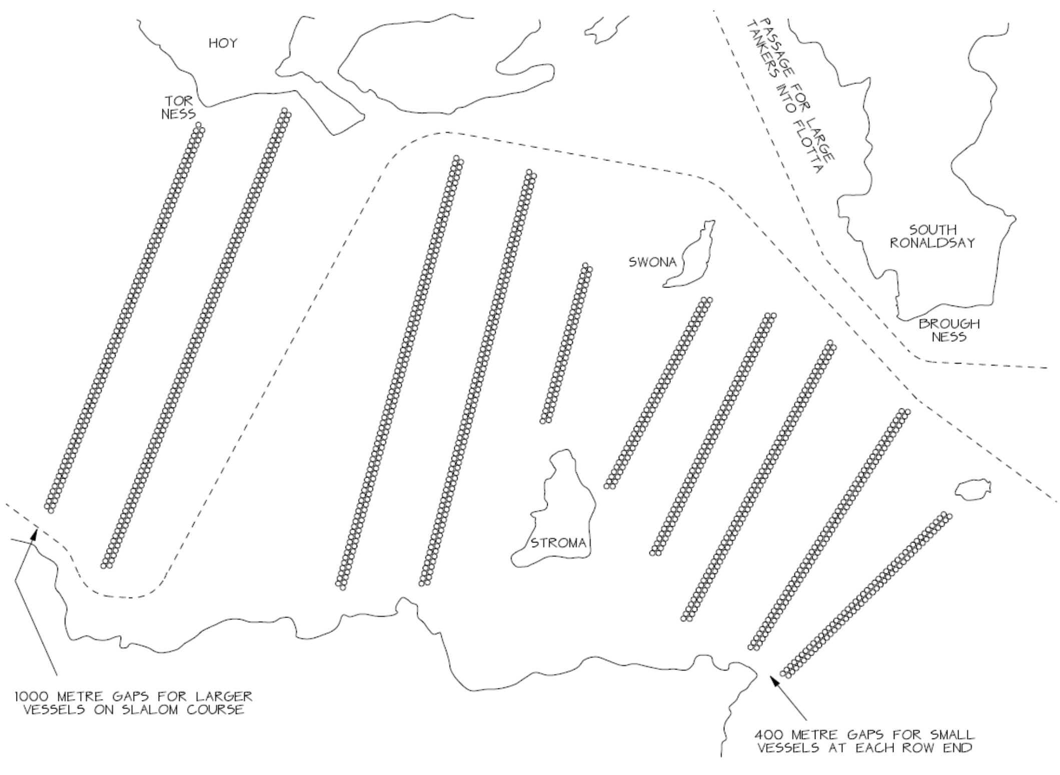

Figure 6. A possible layout of close-packed lines of turbines intended to allow as much freedom for navigation as is compatible with the needs for clean supplies of renewable energy. Comments, however hostile, would be welcome.

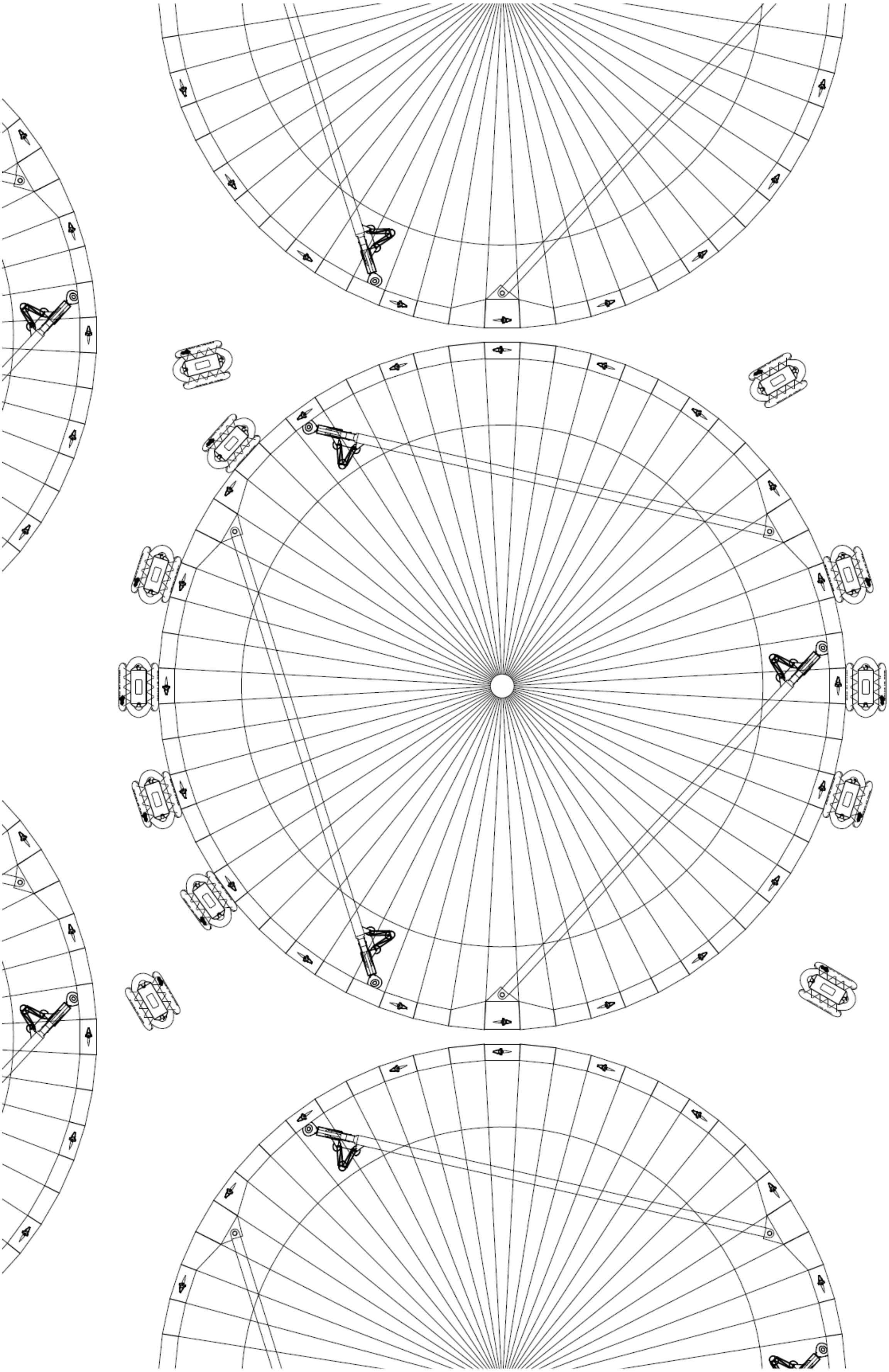

Figure 7. A plan view of close-packed vertical axis rotors and attendant installation vessels. Close packing requires agile changes of force direction from the installation vessels but can be assisted by control of blade pitch in neighbouring turbines. We could even change the flow direction and flush objects to the ends of rows.

4. Seabed attachments

The sea bed attachments have been described previously by Salter and Taylor [9] but, because of possible applications to other wave and tidal stream plant, a repetition here may be useful. The seabed attachment affects the entire design of tidal stream turbines and is highly dependent on local geology. For a vertical-axis rotor we can use a system known as a tri-link which consists of three rigid legs made from post-tensioned concrete with spherical end-bearings and adjustable buoyancy. These are shown in plan in figure 7. They give the rotor freedom to heave, pitch and roll but will prevent surge, sway and yaw. Good tidal-stream sites, which are open at both ends, are likely to be swept clear down to solid rock or very large boulders.

For the easiest case of good rock the preferred choice, shown in figures 8, is a set of three conical fabrications pulled down into a conical crater by post-tensioned steel strands protected from corrosion by alkaline grout. The size of the cone is set by the strength of the rock. For the Pentland Firth the seabed is red sandstone with a bending strength in the plane of the strata of 37 MPa. With a maximum stress of 10 MPa and the pre-stress factor of 0.4, the diameter of a 60 degree cone for a 70 MW rotor would be 4.5 metres. Cones can be made of Cor-ten, a corrosion-resistant but easily weldable steel, with an anti-fouling treatment.

The conical holes in the rock would be produced by equipment mounted on a novel seabed vehicle with eight hydraulic legs any four of which can support it. The frame would be an octagonal ring. The work platform would be fitted with a rock drill which can be inclined at 60 degrees to the horizontal and also rotated about the vertical axis. This would produce a ring of inclined holes which would nearly meet at the centre. These would be filled with explosives. A ring of low energy propellant will produce a bubble curtain to contain the effects of the blast. A similar method can clear debris from the crater.

The outer surface of the lower cone slope would be fitted with stiffeners in the form of lengths of angle iron. They will initially be filled with clay and will later form passages for post-tensioning tendons. Across the cone would be a conical socket, set at an angle to be perpendicular to the mooring leg. The weight of steel would be about 12 tonnes. A float on the top of the cone would give it enough buoyancy to allow placement with an inflatable vessel. The float would be released, and concrete weighing about 20 tonnes would be pumped inside the cone and in the rough spaces between the cone and the surrounding blast-crater in the rock. The total weight will keep the cone and additional tooling in place.

Drilling holes, placement of post-tensioning tendons, insertion of explosives, wire strands, grout, protective grease, collets and tensioning can be done by tooling which can be indexed about the robot's vertical axis. A ring of 49 holes will be drilled through the clay in the angle-iron stiffeners and then a further 20 metres into the bed rock. Eight lengths of 50 mm diameter, 3-metre drill tube will be held in a rotating can like the chamber of a revolver. It would be sequentially fed downward at 30 degrees from the vertical and returned to the drill can when the hole has reached full depth. A design for this machine will be presented in a future paper.

A plastic hose on the indexing head will be fed down to the bottom of the holes and grout pumped in to the bottom three-quarters of the depth of each hole. The rest of the hole and the passages through the cone will be filled with a non-setting alkaline, hydrophobic, conformable paste, perhaps based on lithium grease, with a density above that of sea water. The non-adhesion of the top quarter of the tendons above the grout level is desirable to store elastic energy and maintain a constant tension to avoid fatigue.

The tendons would be 15-mm diameter, seven-strand wire. This can safely be wrapped round and paid out from a 3.5 metre diameter drum but this wire diameter is rather small for a rock drill hole. Therefore three strands will be passed into each of the 49 holes. The odd number means that the holes will miss each other. The final tool on the indexing head will crop the strands, place a triplex collet over their ends, pull them to the working tension and finally fit a protective cap. This complex tool will require advanced robotic techniques but its cost can be written off over many hundreds of installations.

When a leg is in compression the typical maximum force of about 30 MN from a 70 MW rotor will go safely straight down into the rock and increase the compressive stress at the cone-to-rock interface. When a leg is in tension the hold-down force must exceed the vertical component of the leg tension which could reach 20 MN. The system has the same features as a post-tensioned concrete structure and the upward force is supplied by a reduction of the compressive stress between cone and rock. This contact has much less elasticity than the long tendons and so the tendon stress remains constant and fatigue is avoided. Furthermore all tendons will have been fully tested during the post-tensioning process, long before the turbine arrives.

The lower end of each leg will be fitted to the cylinder of a large hydraulic ram. The rod of the ram will be fitted to the outer of a plain spherical bearing such as the SKF GEC 1250 FSA [**10**]. This has a dynamic rating of 35.5 MN and a static rating of 52 MN. It can take rotation of 3 degrees either side of centre.

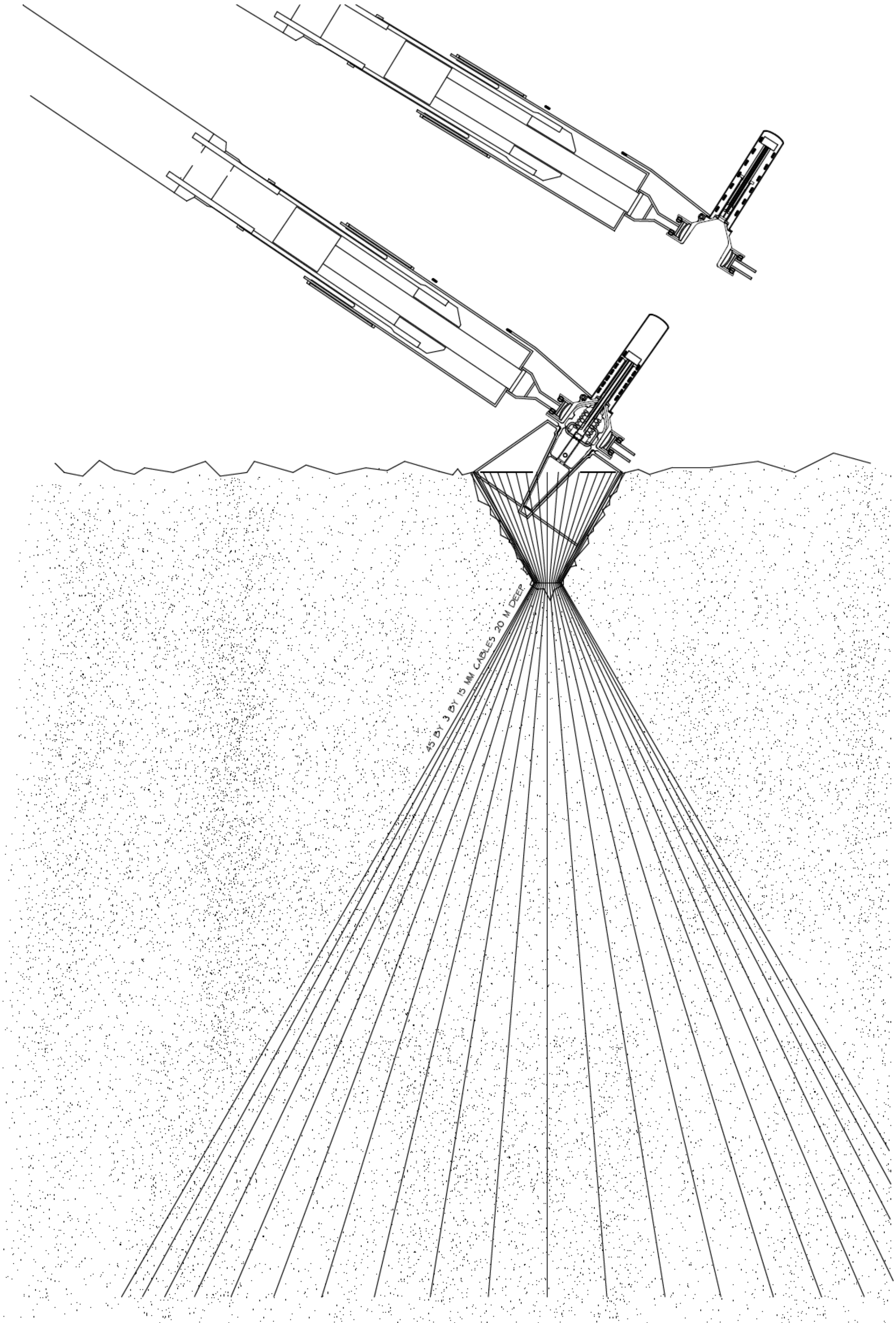

Figure 8. A conical insert is pulled down into a conical hole in the rock by 49 x 3, 15 mm tendons.

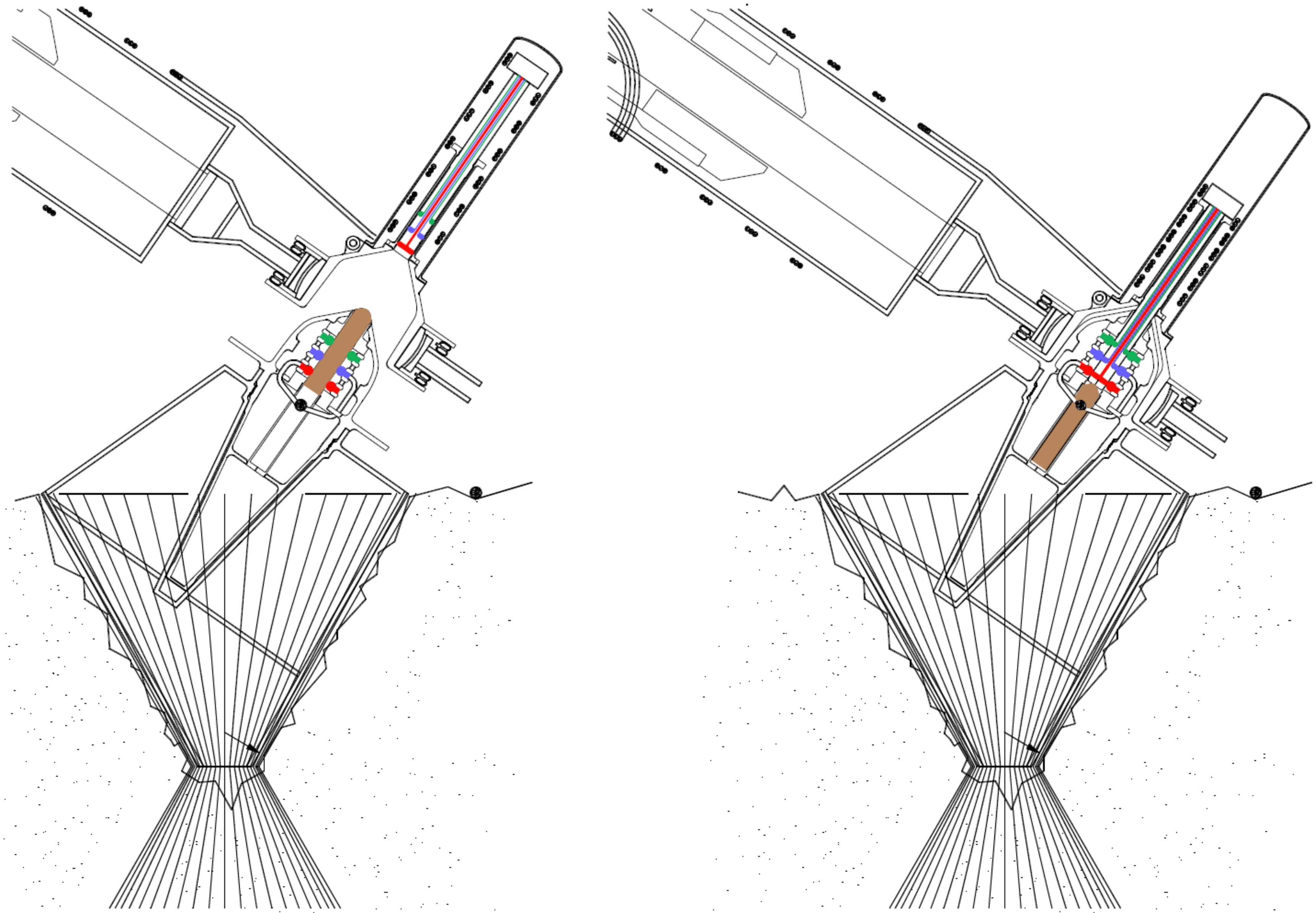

Figure 9. Making the electical connections. To the left the seabed compartment is sealed by the buff plunger and the coaxial 33 kV conducotrs are retracted. On the right after physical contact, flushing and drying the plunger is pushed down by the advancing coaxial conductors.

The pressure in the ram will be an accurate measure of the force on the leg. If oil from each side of the ram piston is fed to the appropriate side of the bearing it can partly offset the contact force without going all the way to the higher leakages of a full hydrostatic bearing. This allows much higher bearing velocities than SKF would like. The small exit flow from the bearing must be scavenged and returned to the system.

The inner of the plain bearing will carry a female cone with a 45-degree half angle which turns into a much more acute angle, probably 2.5 degrees. The choice of this angle is important because it will form the contact with a male cone permanently placed on the seabed. The axes of the cones will lie perpendicular to the direction of the leg. The female cone will contain a set of reinforced-textile air-bags made of a material similar to that used for fire hoses. These will act as cushions when inflated but will vent air and slowly collapse as the cones approach one another. The outer end of the female cone will be bell-mouthed.

5. Installation

Conventional marine installation uses tugs and towlines. An inelastic cable connecting two objects which are far enough apart to be in waves of opposite phase can experience a tension which is the relative separating acceleration, possibly twice the acceleration of the water in a wave, times the mass plus added hydrodynamic mass of the lighter object. Even higher tensions can result if a cable is allowed to go slack and then retighten after the build-up of kinetic energy. An elastic cable can store energy which will be half the square of the peak tension times the spring rate of the rope. If the cable should ever break it will release this stored energy in a frighteningly short space of time.

Cables can apply only tension and in only one direction. They are slow to make changes in that direction. To connect or disconnect heavy cables at sea requires intelligent communication and the control of large forces and heavy objects at both ends of the cable, but vessels in distress often have no power to move heavy objects and sometimes not even a crew. The only attractive things about a cable are that the tug can be at a safe distance from a dangerous client vessel which is burning or about to explode and that the cable can be coiled for compact stowage. Everything else about towing cables is bad.

Conventional tugs must be able to make trans-ocean crossings lasting many days in any weather and must provide acceptable living conditions for quite large crews. This makes hire expensive, typically tens of thousands of pounds a day for an unpredictable number of days. Furthermore availability and hire costs vary widely depending on weather, demands of other work and the location of the tug.

The vessels have to be paid for as they move between jobs and when they have no work. Until the oil has gone, the marine renewables cannot compete with the charter prices of oil firms. A single installation cycle can be a large fraction of initial capital cost and early devices may need many cycles of removal.

A better system would place the tug and the structure being towed close enough to be in the same wave phase and arrange that their phase and amplitude responses to wave spectra are similar. This would produce a large reduction in the forces between them. The driver vessel should be able to apply force in any direction through the shortest possible connecting link and change it quickly. The system should allow instant connection and disconnection with intelligence at only one place and no need for handling heavy weights.

The drag of a hydrofoil at zero angle of incidence is about one-fortieth of the drag of a circular cylinder which would just fit inside it. If the rotor foils are free to point into the direction of the local water velocity, turbines will be quite easy to tow. However with fuel and a Diesel engine on board, a pair of vertical-axis rotors could act like ocean-going vessels with an astonishing bollard pull and extreme agility in any direction. A single rotor could do quite well if fitted with some torque reaction. An installation vessel using very large inflated tubes, GPS-linked 360-degree variable-pitch vector-thrusters and a quick-disconnect magnetic coupling has been described [**11**]. Each can produce a thrust of 200kN so a group of four could install a large rotor, even without assistance from the rotor itself.

Before the installation one inflatable vessel will arrive at the site, where there will be three marker buoys with lines running down to caps protecting the male cones on the seabed. The buoys will be captured and their lines will be made fast to the vessel. The lines will contain air hoses leading to the inside of the caps so that they can be released by compressed air. The arrival of the turbine will be timed for just after the seabed cone-caps have been removed. The turbine will be accurately positioned over its designated site with help from a carrier-phase differential GPS navigation system. Analysis of records from acoustic Doppler instruments shows that several sites never have completely slack water but rotors can ‘hover’ accurately enough for the lower ends to make connection.

When the rotor has reached approximately the correct position and the support vessels have rotated it to the correct azimuth angle, the legs can be lowered by partial filling with water. Three winches will control the lowering of each leg. One winch will take the main weight of the leg. The other two can pull the leg outwards or inwards. The third degree of freedom needed for full positioning control can come from the ram at the lower end of each leg.

The end bearing will be fitted with acoustic sensors to give the final, high-precision position relative to datum points on the male cone.

The rams can allow some inaccuracy in the positioning of the seabed attachment. They can provide controlled yielding to wave loads. They can even generate a moderate amount of wave power from long period swell.

Force from the leg will pass to the seabed through the contact between male and female cones looking like a rather over-designed butterfly net. The female cone will have annular cushion bags from which air will be released during the final approach. The initial force collapsing the cushion bags can come from the weight of the leg. After the 2.5 degree cones are in contact, the space between them will still be full of sea-water containing sediment and animal life. This can be cleared with a flow of filtered sea water and then air, both at pressures set below that which would separate the cone contact. This will be followed by flushing with fresh water to remove salt residue, air to remove most of the fresh water, ethyl alcohol to remove the last of the water and a spray of bio-compatible, electrically insulating corrosion inhibitor. Pressure can then be reduced to the level at the surface allowing the 7 bar water pressure to hold the cone closed against the full leg force with no reliance on friction at the 2.5 degree cone contact. Drying air will be circulated to leave conditions suitable for high-voltage connections.

6. Electrical connection

The proposed transmission voltage is 33 kV, so 70 MW will need 1220 amps per phase. The turbine side of the connection will consist of three coaxial conductors insulated with 18 mm of Teflon leading to three 50 mm thick, 200mm diameter disks with rims machined to 22 mm curvature leaving a 6 mm cylindrical track. This gives a potential contact area of 3700 square mm. If an even contact pressure can be achieved the current density at the contact face will be 0.33 amps per square millimetre. All this will be potted into a 200 mm probe, housed in a tube attached to the top of the female cone.

The seabed side of the connection consists of three hollow annular shells with a wall thickness of 1.5 mm, with a slightly elliptical section having a minor diameter of about 100 mm and an inner major diameter which is 0.1 mm clear of the inner probe assembly. The three shells will be housed within the male cone. A sealing piston-plug with O-rings will block the entry to each side of the electrical contact but can slide towards the seabed side once conditions are dry. Pressure will be applied to the probe in the female cone and will advance it, pushing away the piston-plug which was sealing the male cone. When the disks of the turbine side are aligned with the seabed rings, oil pressure will be applied to the inside of the elliptical section annuli. This will distort them to the circular shape and make a uniform high-pressure contact. The complicated shape of the elliptical section annulus can be made from electroformed nickel. This has a rather high electrical resistivity but plating with 0.2 mm of copper will reduce the dissipation in the annulus to less than 20 watts at 600 amps.

When a turbine has to be removed, air will be pumped into the mooring legs to give them some small positive buoyancy and a tension will be applied by winches on the power torus. Hydraulic pressure applied to the underside of the probe piston will pull it back into its housing dragging the male cone piston-plug after it and leaving both entries sealed.

High pressure air will be injected into the space between the cones to supply a large force to break the contact. It is important that all three legs disconnect simultaneously. The Morse tapers used for large twist drills have half-angles of about 1.5 degrees but, interestingly, are not all quite the same angle. They need a sharp tap to break contact. Such a tap could be provided by an air cylinder driving a hammer head.

We will have to ensure that the cone contact does not corrode while a turbine is absent. It can be protected by lowering a cap in the form of a similar female cone. This can be done by three of the inflatable vessels described above.

Electrical cables and hydraulic hoses which are forced to bend are a notorious source of poor reliability. The problems are invariably found at the ends where bending is concentrated. The problem can be reduced if the cables and hoses are formed into loops of a generous diameter by an 'exo-skeleton' which forces the cable to enter the loop along a defined tangent and spreads the necessary bending evenly over the full circumferential length of the loop by a mechanism at the ends of the rams.

Four metres of ram travel will need a change of about 15 degrees in 2.25 turns of the outer loops and 30 degrees spread over 4.5 turns of the centre loop. If the loops are two metres in diameter these changes in curvature would produce less than 1000 microstrain at the outer sheath of a 50 mm cable. This would be low enough for a steel pipe and should give an infinite fatigue life.

The rod of the ram can be protected by a rubber 'Belofram' *rolling seal* which works like a stocking partly turned inside out. This is contained by a can at the end of the ram rod which runs back over the cylinder body. This rod-can will carry a bearing to allow the ram end to rotate independently of the exo-skeleton linkage so that rolling of the rotor will not be transferred to the seabed attachment. Three helical loops between the legs and the ram end will allow the 33 kV cables and control hoses to tolerate this rotation.

6. Conclusions.

The use of open flow field equations for hydraulic machines in closed ducts can lead to gross underestimates of the potential resource and the wrong designs of turbine. The error could be at least one and possibly nearly two orders of magnitude.

There is great uncertainty about the losses due to bed friction in the Pentland Firth and an urgent need to make accurate measurements of the slope and velocity distribution through the full width and depth.

A head times flow-rate equation leads to less variation in output through the lunar cycle than a velocity-cubed one.

There is a phase lag of about 60 degrees between slope and the flow velocity at the centre of the channel. This suggests than some reactive tuning may be useful to bring the natural period closer to the main M2 driver and may bring a further increase in resource size.

If the Pentland Firth can be regarded as a high impedance flow source then we should use turbine designs which fill a large fraction of the flow window. This favours vertical axis configurations using as much as possible of the 70-metre depth and the use of post-tensioned tri-link legs for the sea bed attachment.

A large installation will have a serious impact on the free passage of shipping through the Pentland Firth but consultation and intelligent planning can minimize the interference.

The similarity between the vertical axis turbine and the Voith-Schneider propeller suggests that self-installation with assistance from light vessels to provide a torque reaction should be possible provided that we can design quick connections and disconnections for both mechanical force and multi-megawatt electrical power.

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