An experimental study to assess the potential benefits of foundation based flow acceleration structures for marine current energy converters

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Abstract

This paper presents a preliminary experimental study investigating the potential benefits of foundation based flow acceleration structures for marine current energy converters. Foundations would provide multiple benefits, including; increased device power output, increased foundation footprint and scour hole protection.

Experiments, scaled from a shallow tidal flow site, provide evidence that these structures could give power benefits of 12-25% depending on ramp size and flow depth. An optimum ramp size was established based on the suitability of vertical velocity profiles for energy extraction.

Keywords: Tidal flows, flow acceleration, ramp foundation, power gain, velocity profile, ADV

Nomenclature

C_p	= power coefficient
ρ	= water density
V_0	= rotor centre flow velocity
A_d	= turbine swept area
F_d	= Froude number
d	= flow depth
d_1	= upstream flow depth
d_2	= flow depth across ramp
V_1	= upstream depth averaged velocity
V_2	= depth averaged velocity across ramp
ΔZ	= ramp foundation height
L	= ramp length
W	= ramp width
H	= ramp height
I	= ambient turbulence intensity
σ	= standard deviation of sample
U	= 3D mean velocity of sample
X, Y, Z	= instantaneous velocity
$\overline{X}, \overline{Y}, \overline{Z}$	= sample mean velocity

$X' = X - \overline{X}$

$Y' = Y - \overline{Y}$

$Z' = Z - \overline{Z}$

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1 Introduction

A critical limiting factor for the commercialisation and deployment of large scale tidal energy is the availability of suitable sites. Suitable locations need to be easily accessible for device installation and maintenance, close to grid connections and most importantly have sufficient tidal flow velocities. Power from a tidal turbine is proportional to the flow velocity cubed; hence any small increase in velocity will result in considerable power benefits [1].

$$power = \frac{1}{2} C_p \rho V_o{}^3 A_d \quad \textbf{(1)}$$

Many suitable sites for marine current energy converters (MCECs) are located in shallow tidal flows such as those found close to the shore and in estuaries. Shallow flows may have reduced tidal velocities, compared with deeper channels, but they have other benefits including close location to the shore with many sites situated away from shipping channels. This could make construction and grid connection both easier and economically feasible. Regions of flow that presently have insufficient velocities for economic power generation could be made economically viable with the use of artificial flow acceleration structures.

Ramp or apron structures placed on the seabed could be used to locally accelerate the flow whilst also offering scour protection and an increased foundation footprint (Fig 1). Increasing the footprint area would increase the downforce created by the foundation and hence increase the bed shear capacity. With careful design of the leading edge it may also be possible to smooth the vertical velocity profile that will serve to reduce rotor loading. These structures would form an integral part of the MCEC foundation and would be most applicable to shallow tidal flows with depths ranging from 10 to 15m. Foundations could be gravity based and constructed using reinforced concrete caissons which are floated out from shore and sunk in the required position. The concept could be used for deeper flows but ramp height would need to be considerably greater to accelerate the flow, hence leading to increased construction cost.

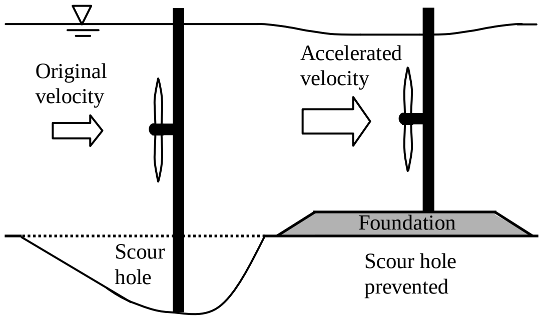

Figure 1: Proposed ramp foundation benefits.

It may seem intuitive that a ramp spanning the full channel width will accelerate the velocity; in reality however it would not be feasible to construct a ramp which spans the entire width of a tidal channel. The ramp foundation would only occupy a small proportion of the channel hence the interaction effects of the bounding flows are critical. In addition, minimising the ramp's dimensions will reduce the construction costs and improve concept viability.

For efficient energy capture the vertical velocity profile ideally needs a vertically linear upper section to reduce cyclic rotor loadings [2]. Vertical velocity profiles have been measured at a few locations in UK waters [3-4]. One of these shows a very close resemblance to the modified $1/7^{th}$ power law [5], with a sheared boundary layer region near the bed and an approximately linear upper section. When the flow encounters the upstream edge of a ramp structure the lower sheared section of the vertical velocity profile will effectively be removed [6] and the profile will start to re-develop across the ramp. Fig 2 shows some measured vertical velocity profiles across a scaled ramp in a water channel facility. Ideally the MCEC would be located at the optimum location along the ramp where the maximum velocity increase occurs coupled with a more uniform vertical profile.

It is preferable to avoid the sheared region of flow near the sea bed as the differing mass flow rates will cause disparate rotor loadings. It has been previously estimated that the top 8m and bottom 25% of the depth should be avoided due to surface wave effects and the steeper section of the boundary layer respectively [5]. It is also important to ensure the ramp will not induce more turbulence which could have a negative effect on MCEC loading and performance.

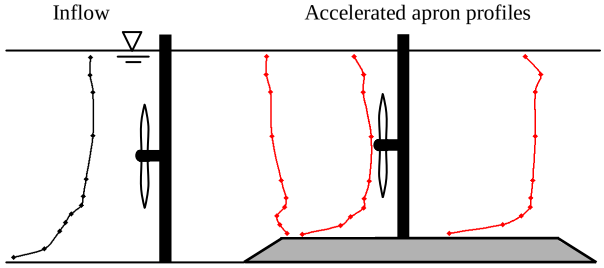

Figure 2: Boundary layer re-development.

When analysing the flow using specific energy estimations a significant surface drop would be expected across the ramp. However results from previous work indicate that unless flow speeds become very rapid and the flow is confined by solid boundaries there may not be any measurable change in water surface elevation [7].

$$surface\,drop = d_1 - d_2 = \frac{V_2^{\,2}}{2g} - \frac{V_1^{\,2}}{2g} + \Delta Z \quad \textbf{(2)}$$

As with any new concept the cost/benefit will be important to the commercial viability. The construction of an extensive ramp foundation will add cost to the construction and this added cost must be recouped in the additional power generated and through reduced construction costs associated with any reduction in dynamic loading offered by the ramp.

2 Materials/Methods

In order to test the concept at a manageable scale, scaled ramps were constructed and tested in a circulating water channel at the University of Southampton, UK. The working section of the channel is 21m in length, 1.35m wide and a maximum 0.4m depth for steady operation with a maximum flow rate of $0.2m^3/s$.

Using Froude scaling, the experimental flow domain was scaled from a prototype MCEC deployment site with an average full scale depth of 10m. Spring peak and neap peak tidal flow velocities are in the range of 0 – 2m/s. It was assumed that a feasible full-scale ramp foundation height would be 1m.

A range of different flow parameters and ramp dimensions were investigated. These included varying; Froude number, ramp height to flow depth ratio, ramp width and length. The angled sections at the upstream and downstream ramp ends are termed “approach ramps” and were angled at 30 degrees to the horizontal. A streamlined rig was used to fix the ramps to the channel bed.

A range of flow and ramp configurations were tested, however only a limited number are included in this paper for clarity, dimensions are shown schematically in Fig 3 and tests are detailed in Table 1.

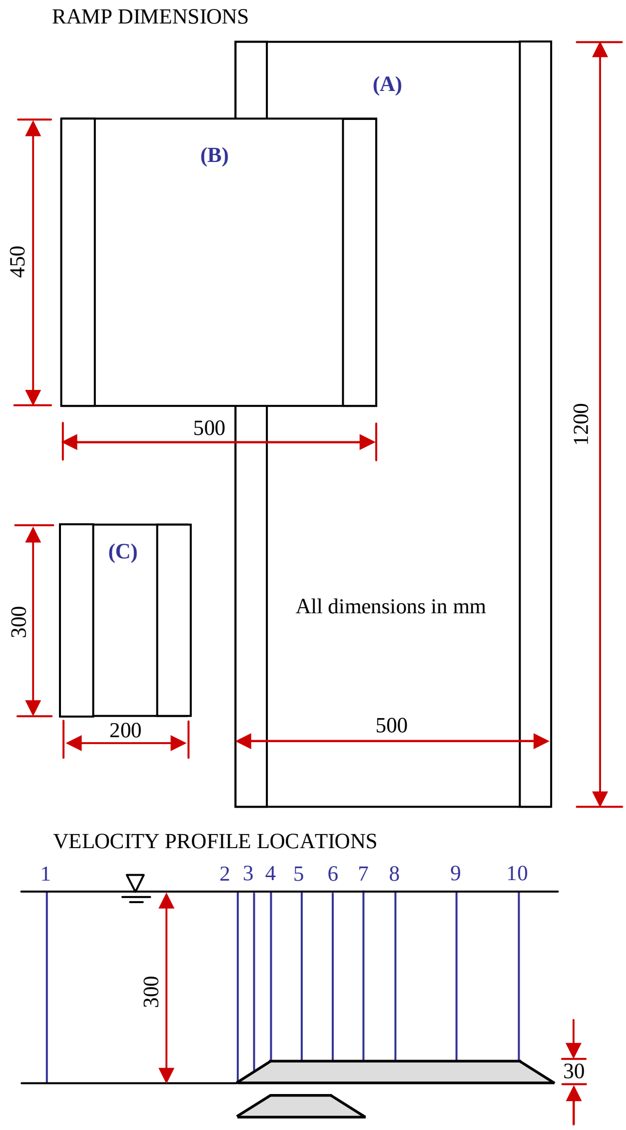

Figure 3: Ramp dimensions and velocity profile locations.

To determine the potential benefits of the ramp, velocity profiles were measured upstream of the ramp and at various locations along the ramp’s length; numbered in Fig 3.

In order to measure the velocity profiles and visualise the flow field around the ramps, samples were taken using a high frequency Nortek Vectrino Acoustic Doppler Velocimeter (ADV). Operational issues and the accuracy of ADVs has been addressed at length in many publications [8-11]. The Vectrino ADV was set to sample at 50Hz. For each data point 7500 readings were taken over a 150 second period.

Test	F_d	**d [mm]**	**Scale ramp [mm]**			**Ramp**	**Full scale [m]**		
			L	W	H		L	W	H
1	0.25	300	500	1200	30	A	16.5	40	1
2	0.20	300	500	1200	30	A	16.5	40	1
3	0.20	400	500	1200	30	A	16.5	40	1
4	0.20	200	500	1200	30	A	16.5	40	1
5	0.20	300	500	450	30	B	16.5	15	1
6	0.20	300	200	300	30	C	6.6	10	1

Table 1: Experimental parameters and full scale dimensions.

Data was filtered to remove noise and spurious points although the large quantity of suspended particles in the circulating channel minimised sample errors. Filtering is required to improve measurements of higher order flow effects such as turbulence intensity and shear stresses. However filtering has a very small effect for mean flow velocities. There are many methods for filtering data but the Velocity correlation filter, described in [12], was chosen. This method plots the components of velocity against each other and constructs an ellipse to exclude any data points that deviate significantly from the sample mean (Fig 4).

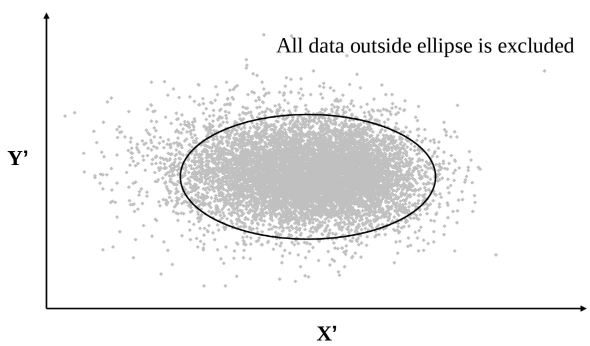

Figure 4: Velocity correlation filtering method.

For good quality scaled experiments the full scale environment must be accurately replicated [13]. Of particular importance is:

1. Accurate linear scaling of ramp dimensions.

2. Ramp height to flow depth ratios.

3. Replication of ambient flow field conditions, including: Froude number, vertical velocity profile (approx $1/7^{th}$ power law) and turbulence intensity.

When conducting small scale tests in a circulating water channel, there will be limitations. These include replicating full-scale channel bathymetry, the temporal dynamics of a tidal cycle (such as varying depth, flow velocity and direction), lateral blockage effects and Reynolds and Froude number parity. These parameters must be considered when interpreting results but should not effect the general conclusions presented in this paper and it would be virtually impossible to fully represent all the features found in a natural tidal channel at this scale. It will not be possible to achieve Reynolds number parity between model and full scale although for the experimental tests presented here the model Reynolds number was fully turbulent. Lateral blockage is of concern but the channel is significantly wider than it is deep so effects should be negligible.

Characterisation of ambient turbulence levels is important as long length scale turbulence may lead to increases in dynamic rotor and structure loading. The ambient turbulence intensity in the circulating channel is approximately 6-7%. Ambient turbulence intensity was calculated in all three planes (X,Y,Z) and is defined as:

$$I = \frac{\sigma}{U} \tag{3}$$

High shear stress can be detrimental to MCEC survival. Horizontal shear stress should be approximately zero throughout the channel depth as lateral velocity components are small. Vertical shear stress will increase towards the channel bed due to increased shear in the boundary layer. Horizontal and vertical shear stresses are defined as:

$$\text{Horizontal Shear Stress} = X'Y'\rho \tag{4}$$

$$\text{Vertical Shear Stress} = X'Z'\rho \tag{5}$$

Non-dimensional results for velocity measurements and turbulence intensity are presented by normalising ramp profiles with the depth averaged values from the upstream profile.

Figure 5: Scaled foundation ramps:
Width: 1200mm (top) & 450mm (bottom).

3 Results

Full channel width ramp:

The initial set of tests involved a ramp spanning the full channel width. A range of Froude numbers with a fixed flow depth of 300mm were investigated. Velocity profiles were taken at the locations detailed in Fig 3.

Fig 6 shows how the X-plane velocity profiles developed across the ramp for a flow depth of 300mm and a Froude number of 0.25. The profile taken 150mm downstream of the ramp front edge shows the best profile for energy extraction, in terms of acceleration and a linear upper section. The sheared boundary layer region does not seem to increase considerably with the presence of the ramp. In general these conclusions are true for all tests conducted with the full width ramp at a flow depth of 300mm. The X-plane velocity was increased by approximately 10% in all cases.

Velocities in the Y-plane (lateral) and Z-plane (vertical) were found to be approximately equal to zero throughout the flow depth. With the exception of the profiles taken across the upstream approach ramp where small Z-plane velocity components were introduced near the ramp. This is likely to have resulted from a small back eddy forming at the start of the ramp.

Turbulence intensities reduced slightly across the ramp for all planes (X,Y,Z). This is very significant because, as previously stated turbulence can have negative effects on MCEC performance. It is postulated that the acceleration in flow speed may have removed some of the turbulent motion.

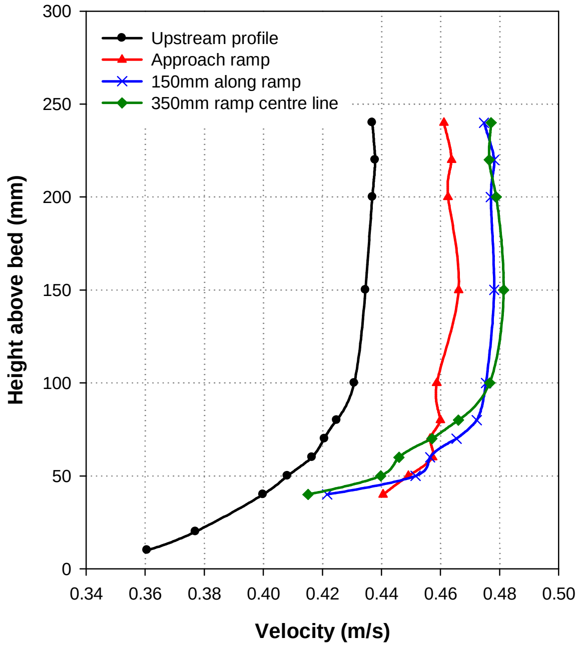

Figure 6: X-plane velocity profiles:
Full channel width ramp, $F_d = 0.25$, d = 300mm.

The horizontal and vertical shear stresses were calculated throughout the water depth. Horizontal shear stress was found to be approximately zero throughout the depth. This was expected as there are no significant lateral components of velocity to cause shear in this direction.

Fig 7 gives an example of typical measured vertical shear stress profiles. Shear stress increases towards the bed and values are slightly higher across the ramp; however, as stated previously this does not appear to adversely affect the vertical extent of the sheared boundary layer.

A series of tests were run to investigate the effects of changing the ramp/flow depth ratio.

$$ramp/depth\,ratio = \frac{ramp\,height}{flow\,depth} \qquad \textbf{(6)}$$

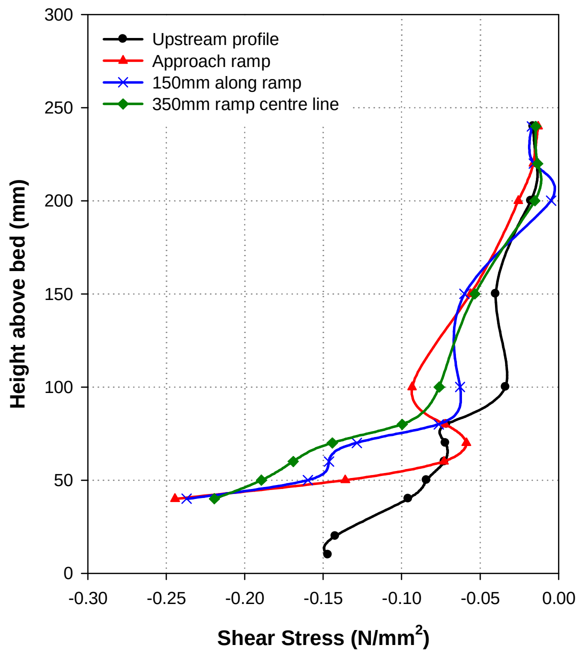

Figure 7: Vertical shear stress:
Full channel width ramp, F_d =0.25, d =300mm.

Here the ramp height was kept constant, but the flow depth in the channel was varied. The results are illustrated in the non-dimensional graphs (Fig 9-12). It can be seen that if the ratio is increased (i.e. flow depth reduced) the benefits of the ramp are greater in terms of velocity gain. If the ratio is reduced the velocity gain decreases. This highlights the fact that this technology might be difficult to implement in deep tidal flows because ramp height would need to be considerable.

The varying ramp/depth ratio experiments were conducted with ramps effectively spanning the whole width of the channel. In reality this is unlikely to occur. A final set of experiments were conducted to understand the effects of reducing ramp width and length.

Ramp width and length reduction:

Ramp length and widths were progressively reduced to establish an optimum ramp size and to understand the effects of the ramp side edges on the flow.

In general the conclusions from the full width tests held but with the benefits reduced. Fig 8 shows the X-plane velocity profiles from the smallest of the ramps tested. For this setup velocity was still accelerated but by only 5%.

For all the tested ramps at a flow depth of 300mm the optimum vertical velocity profile remained at 150mm downstream (or 6 ramp depths) from the leading edge of the ramp. However for the smallest ramp this point is at the very end of the ramp, so it can be concluded that this ramp was insufficient in length. The optimum ramp length would thus be 300mm so that the optimum profile will occur at the ramp centre line allowing a device to benefit from the increased energy flux from both directions in a bi-directional tidal flow. This would equate to a 10m long ramp at full scale.

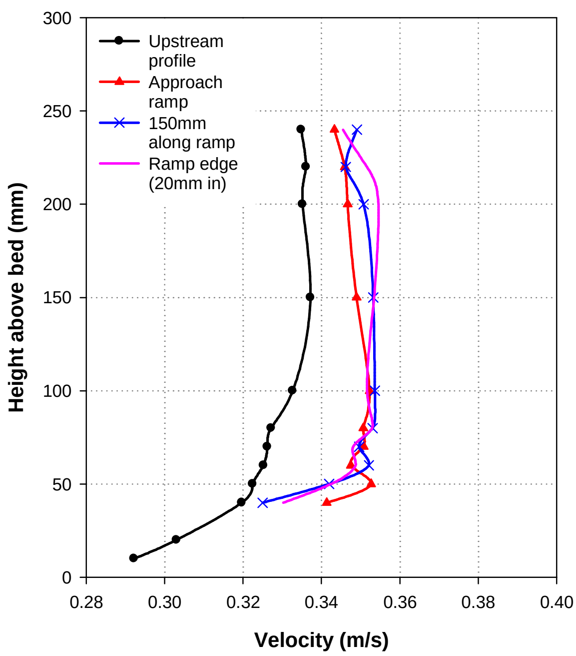

Figure 8: X-plane velocity profiles:
(L)200mm x (W)300mm ramp, F_d =0.20, d =300mm.

There were no significant velocity reductions seen near the side edges of the ramp (Fig 8). Some side edge velocities were slightly reduced, however this would be expected as velocity generally reduces away from the channel centreline. This would mean full scale ramps would not need to exceed the device width, reducing construction costs.

At Froude numbers of approximately 0.2 there was no observed change in water surface elevation over the apron structure. According to equation 2 a reduction in water surface elevation should occur for subcritical flows (F_d.<1) leading to a even shallower and faster moving flow over the apron. However, this is clearly not observed by experiment under what are relatively and hydraulically defined as tranquil conditions. It is expected that Froude numbers approaching 1 (or critical condition) may be required in order to observe and quantify any reduction in water surface elevation over the apron structures. This could be achieved by increased flow speed or a reduction in total water depth.

Optimal downstream distance for energy extraction:

Fig 9 shows a normalised comparison between point 4 located at the top of the approach ramp. It shows how the sheared boundary layer is initially removed by the ramp to give an almost completely vertical profile. This would be an ideal profile for energy extraction; however the velocity is not yet fully accelerated and power gains would be less.

Fig 10 shows velocity profiles taken at the optimum energy extraction location. It highlights how increasing the ramp height/flow depth ratio increases the velocity gain and how reduced ramp size reduces the velocity gain. Profiles exhibit compressed sheared boundary regions and good vertical profiles for energy extraction.

Turbulence intensities showed similar trends for all tests (Fig 11 & 12). Both the X and Y-plane profiles were an inverse of the X-plane velocity profile with a constant upper section equal to 6-7%. Z-plane turbulence intensity was generally constant with depth, with slightly lower values of approximately 5%. Fig 11 & 12 shows how the turbulence intensity was less across the ramp compared with the average upstream values.

In essence the lower section of the flow depth should be avoided for energy extraction for both increased shear stress and turbulence intensity.

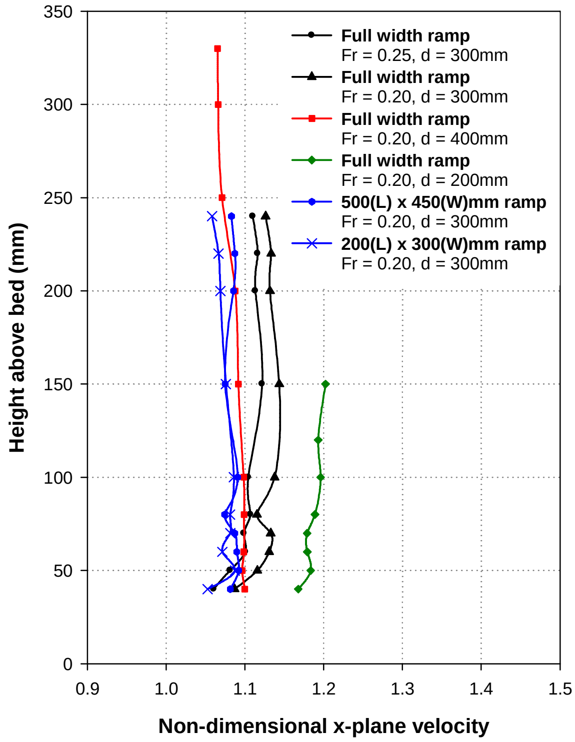

Figure 9: Non-dimensional X-plane, point 4, velocity profiles: top of approach ramp.

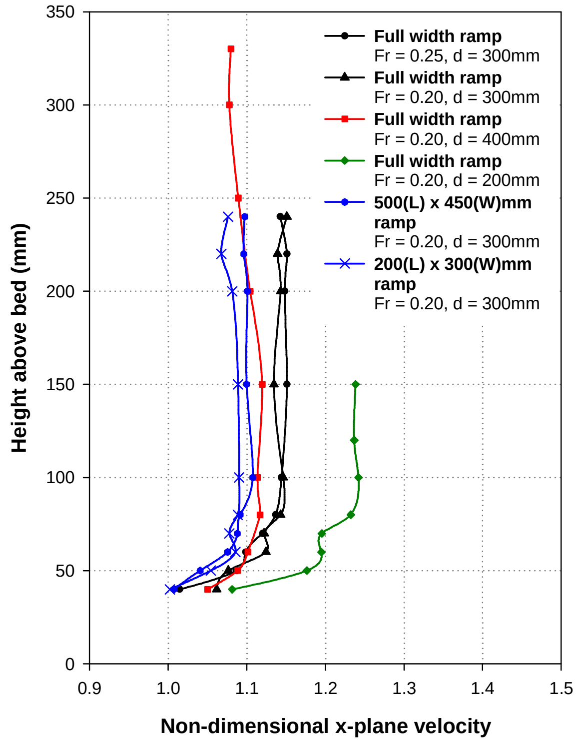

Figure 10: Non-dimensional X-plane, point 6, velocity profiles: 150mm along ramp.

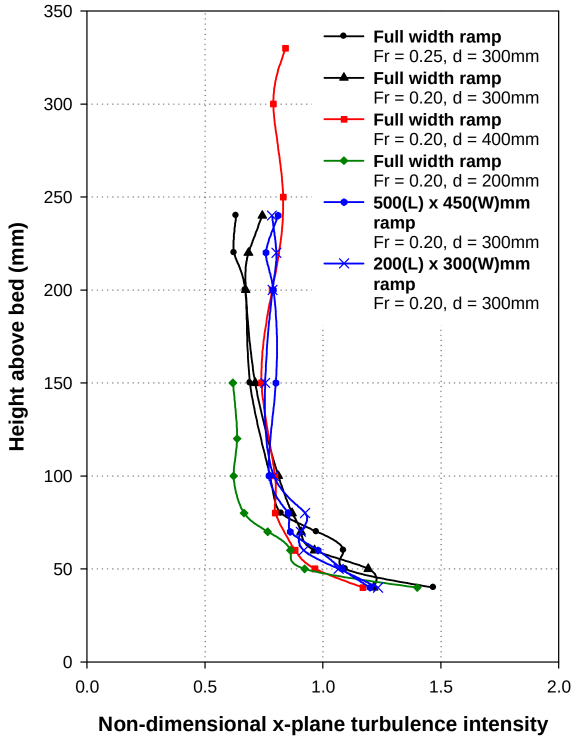

Figure 11: Non-dimensional X-plane, point 6, turbulence intensity: 150mm along ramp.

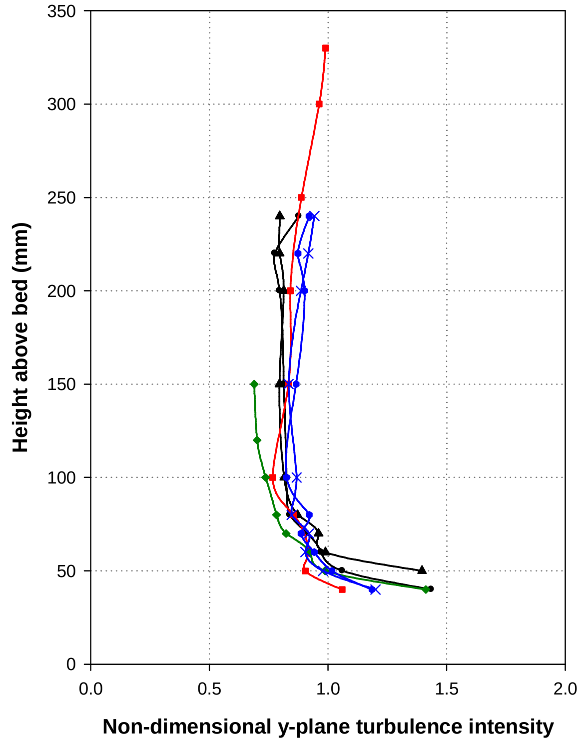

Figure 12: Non-dimensional Y-plane, point 6, turbulence intensity: 150mm along ramp.

Velocity intensity visualisation:

The contour plots given in Fig 13 illustrate how the centreline velocity intensity increases across the ramps compared with the upstream profile. The optimum energy extraction point is shown and the re-development of the boundary layer along the ramp can be clearly seen.

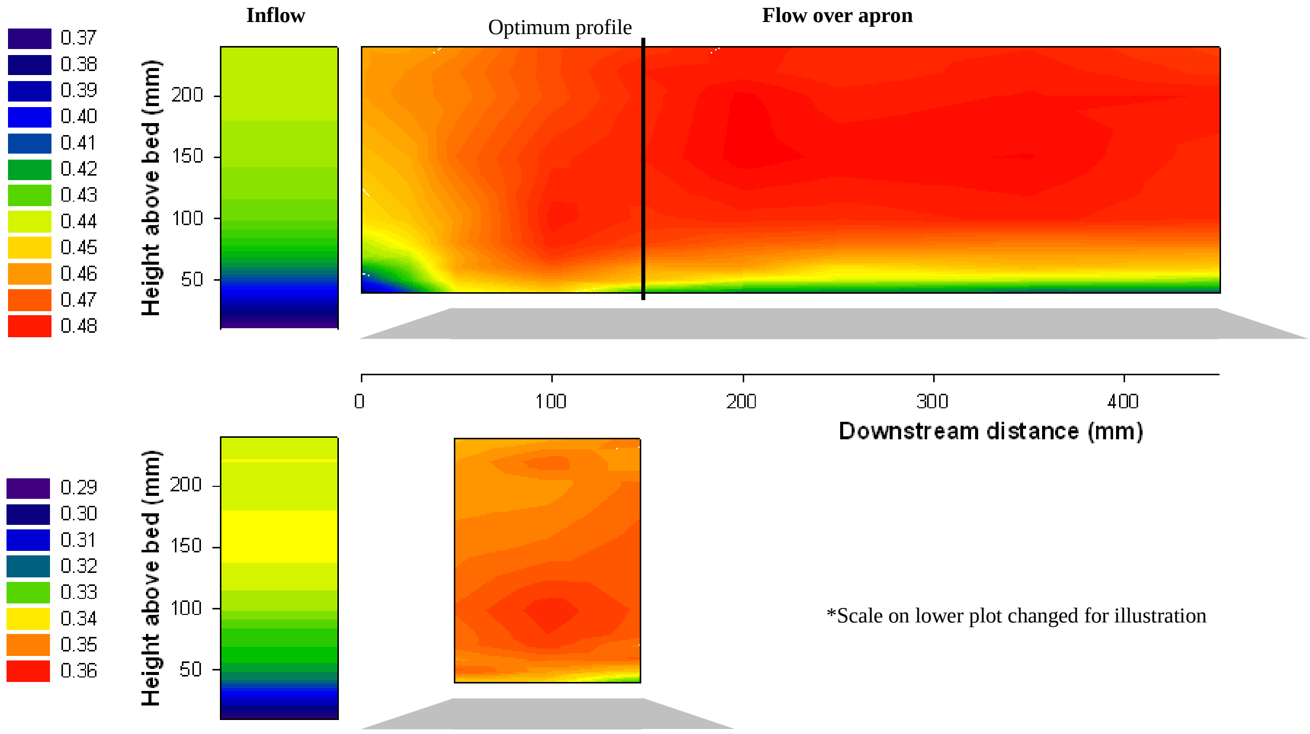

Figure 13: Velocity intensity (m/s) upstream and across ramp. Full width ramp (top). 200x300mm ramp (bottom)

4 Full Scale Application

The experimental findings were scaled to the full scale tidal site. The benefits of an integral concrete ramp foundation are illustrated by calculating potential power gains obtainable from a 5m diameter horizontal axis marine current turbine. Taking into account that the top and bottom 25% of the flow depth should be avoided.

Power was calculated using the power equation (1) and a power conversion efficiency factor of 0.4 was assumed. Results are illustrated in Fig 14.

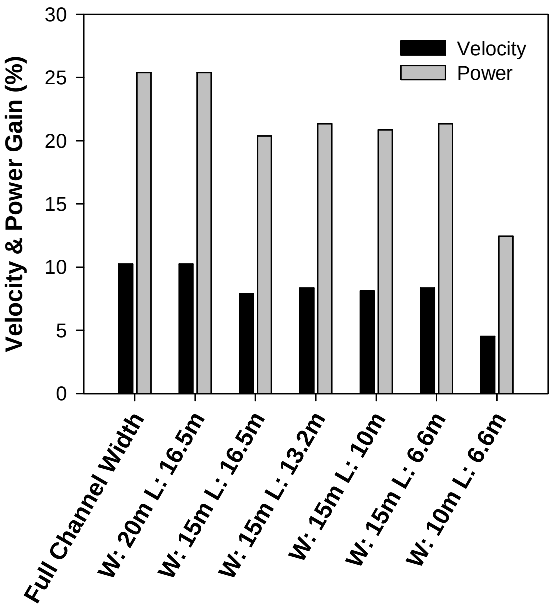

Figure 14: Potential velocity and full power percentage gain.

Interpretation of the results clearly shows for a small velocity gain the resulting power gains are considerable. Even for the small ramp, 12% power gains could be obtained.

5 Conclusions

Ramp foundation structures could be utilised to accelerate tidal flows and increase MCEC power output. These power benefits could be in the region of 12-25%, depending on the ramp size and ramp height/flow depth ratio.

It was found that there was an optimum ramp length depending on the ramp height/flow depth ratio. For a ramp height of 1m and a 10m tidal flow depth this would be approximately 10m.

The width of the ramp would not need to considerably exceed the width of the MCEC, as no significant velocity reductions were recorded near the ramp side edges.

The extent of the sheared boundary layer region does not significantly increase with the presence of a ramp foundation; it is effectively compressed by the increased flow velocity.

Turbulence intensities were slightly reduced in the flow across the ramp, which would be beneficial to device operation and survival.

This concept would probably only be commercially viable for shallow tidal flows and the ramp would need to be of multi-use. This means in addition to increasing device power output, it would also need to act as an integral foundation and scour protection.

This work is a preliminary study and future work aims to address the effects of changing approach ramp profiles, further studies into varying the ramp height/flow depth ratio, effects of yawed flow (as tidal flows are seldom bi-directional), ramp roughness, construction techniques, modelling with computational fluid dynamics (CFD), effectiveness over a full tidal cycle with varying water depth and tidal flow velocities and techno-economic analysis to establish the commercial viability of such structures.

Acknowledgements

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