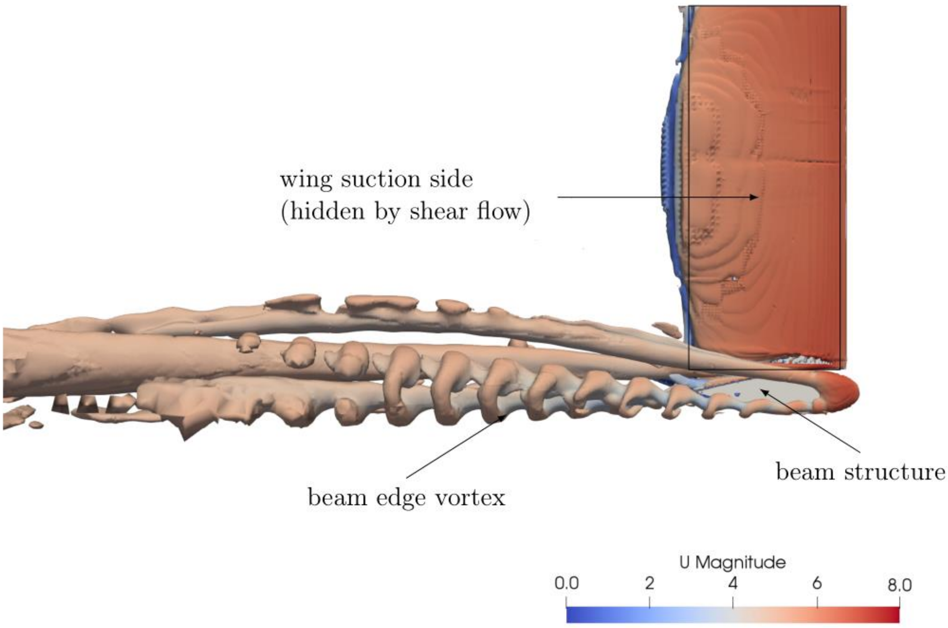
The Seaqurrent TidalKite^{TM}:

Evaluating the risk of seafloor disturbance



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Contents

Summary

In this report we have evaluated the risk of disturbance of the seafloor by the Tidalkite of the company Seaqurrent. Therefore a series of flowtank measurement at the facilities of the University of Groningen were combined with two different computational fluid dynamics (CFD) studies. Measured and modelled kite induced shear forces were compared with critical bed-shear stress data from the literature. All studies showed that the shear forces caused by a moving kite are very low. Highest shear forces induces by a moving kite (at 25 cm distance) were still 50 times smaller than the lowest critical bed-shear stress value reported in literature. This implies that if the kite is travelling horizontally it will not disturb the seafloor.

Introduction

The company Seaqurrent is developing an underwater kite system to harvest energy from low-speed tidal currents (up to 2 m/s). The Tidalkite^{TM} is designed to use the tidal force in relatively shallow waters (< 10 m depth). It travels along horizontal paths parallel to the seafloor at speeds up to 5 m/s. A pulling force acting on a tether is used to generate electricity (Fig 1).

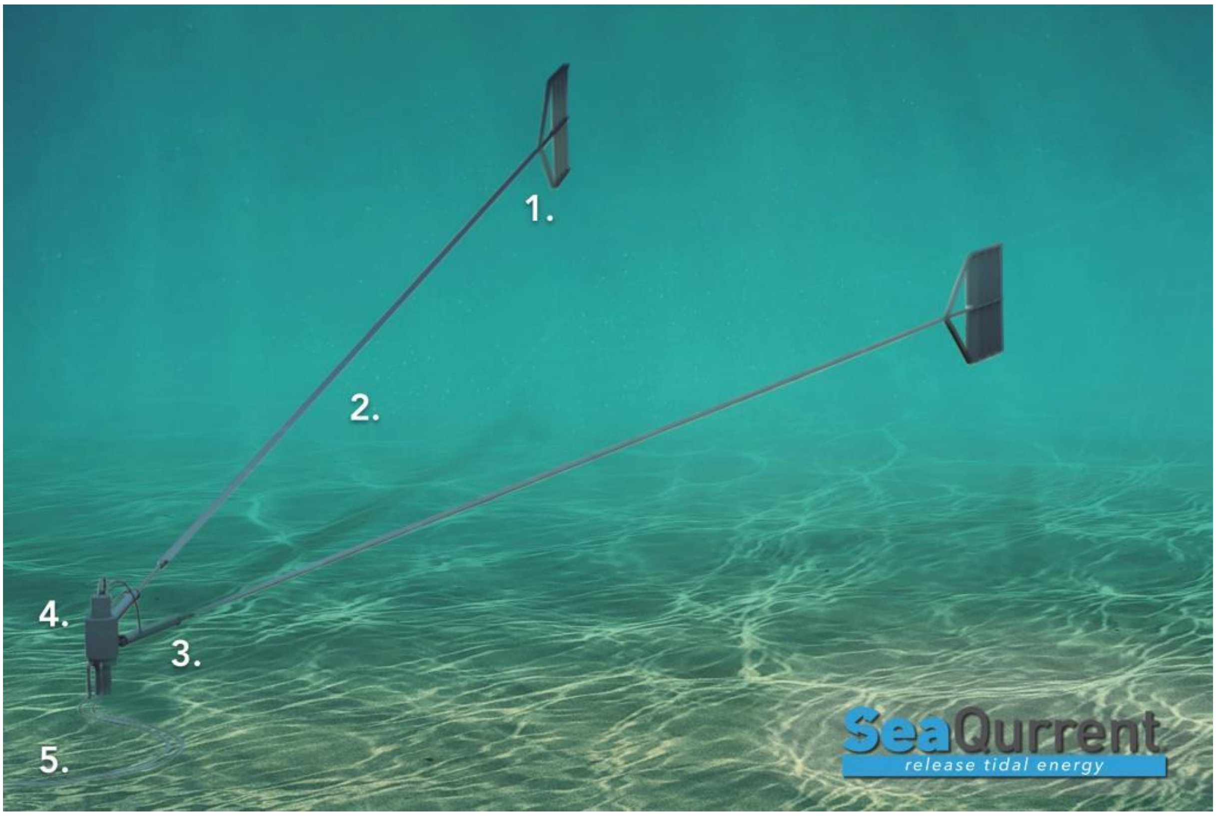

Figure 1: The SeaQurrent TidalKite in a double configuration (2 kites at one mooring point). Legend: 1 = the TidalKite, a series of wing-like structures in a frame; 2 = the tether transferring the pulling force to a hydraulic power-take-off; 3 = hydraulic power-take-off system; 4 = mooring; 5 = seafloor.

In this report we evaluate the risk of disturbance of the seafloor by the Tidalkite. A moving kite could possibly interfere with the seafloor by means of disturbed water stirring up the sediment.

To investigate this scenario, a series of experiments were carried out in the large flowtank (see Methods) from the department of Ocean Ecosystems (Energy and Sustainability Research Institute) of the University of Groningen. These experiments were combined with computational fluid dynamics (CFD) to unravel the effect of a moving TidalKite on the external flow field.

From the flow velocity gradient around the moving kite it is possible to calculate the shear forces (shear stress) around the kite. The shear stress caused by the kite will be high nearby the kite and decrease to zero with distance, so will be lower when further away from the kite.

These shear forces were compared with critical bed-shear stress data from the literature. Critical bed-shear stress is defined as the shear stress value (in $N.m^{-2}$) at which erosion (i.e. movement of clay, silt or sand particles) of a certain sediment takes place (van Rijn 2007). If the calculated shear stress at the distance kite – seafloor is higher than the critical bed-shear stress, disturbance of the seafloor is likely.

Methods

2.1 Measuring shear stress and thickness of boundary layer in ESRIG flowtank

Experiments were carried out in the large flow-tank (Fig. 2) from the department of Ocean Ecosystems (Energy and Sustainability Research Institute) of the University of Groningen. The flowtank measuring section has a cross section of 0.4 x 0.4 m with a length of 1.2 m. Five different flow velocities between 0 and 1 m/s were tested and each measurement was repeated three times. Digital Particle Image Velocimetry (DPIV) was used to get high resolution flow velocity vector information of a whole plane in the flow-tank (Thielicke and Stamhuis 2014). The shear stress (τ) at a certain point from the wall was calculated from flow velocity profiles as the product of the dynamic viscosity μ and the velocity (u) gradient in the vertical direction (x):

$\tau = \mu * \partial u / \partial x$

The thickness of the boundary layer was defined as the distance from the wall where the flow velocity was 99% of the maximal flow velocity (Schlichting, 1979).

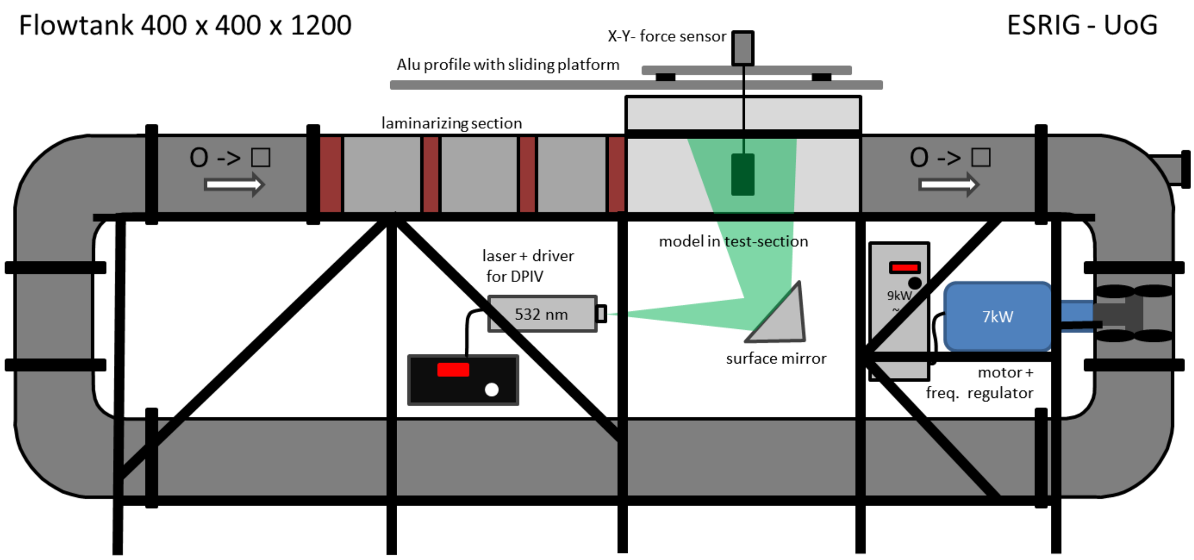

Figure 2: schematic diagram of the flowtank at the university of Groningen

2.2 Computational fluid dynamics (CFD): 2D Single-Phase Flow

Flow velocity profiles were simulated using COMSOL Multiphysics 5.2a software.

Flow profiles were calculated assuming no-slip wall conditions for the following flow speeds: 0.16 m/s, 0.39 m/s, 0.52 m/s, 0.68 m/s, 1.02 m/s and 6 m/s, representing Reynolds numbers of $1.6*10^5$, $3.9*10^5$, $5.2*10^5$, $6.8*10^5$, $1.0*10^6$ and $6.0*10^6$ assuming a characteristic linear dimension, here chord length of the kite, of 1 meter. The 6 m/s was added to the experimental velocities because it is the intended travel speed of the TidalKite.

Two different COMSOL simulation settings were used: the Laminar Flow simulation and the Turbulent Flow simulation according to the k-ω model using Reynolds-averaged Navier-Stokes

(=RANS) method. Bothe simulations were used as analysis of stationary circumstances (i.e. not dynamic).

The calculated boundary layer thicknesses and shear stress values appeared to be slightly higher using the Turbulent Flow model compared to the values calculated using the Laminar Flow model. On top of that, in all cases the Reynolds numbers are relatively high and turbulent flow is most likely to develop in all simulated circumstances. Therefore, only the results of the Turbulent Flow model are shown in the Results section.

Shear stress profiles and boundary layer thicknesses were calculated from the flow velocity profiles as described above.

2.3 Computational fluid dynamics (CFD): 3D visualization of wake structures

A visualization of highly resolved wake structures generated by interference of a TidalKite beam and wing dragged through water at 5 m/s was computed using OpenFOAM CFD software as described by Weiler & Stamhuis (2019). Shear stress profiles were calculated from the derived data as described above.

Results

Boundary Layer mapping:

The measurements in the flow-tank as well as the results from the model calculations show that at all flow velocities the thickness of the boundary layer is only a few centimeters (Fig 3, Fig 5 and Table1). Within 5 cm of the wall (i.e. the kite) water velocity is already close to or higher than 99% of the free-stream flow velocity, by which the boundary layer is defined (Schlichting, 1979). Shear stress calculations also demonstrated that after a few centimeters the impact of the kite is very low (Fig 4, Fig 6 and Table 1). Model calculations as well as measurements demonstrated that all shear stress values at 1 cm distance from the kite are lower than 0.059 $N.m^{-2}$. Shear stress values at 5 cm distance from the kite are approaching zero (< 0.003 $N.m^{-2}$).

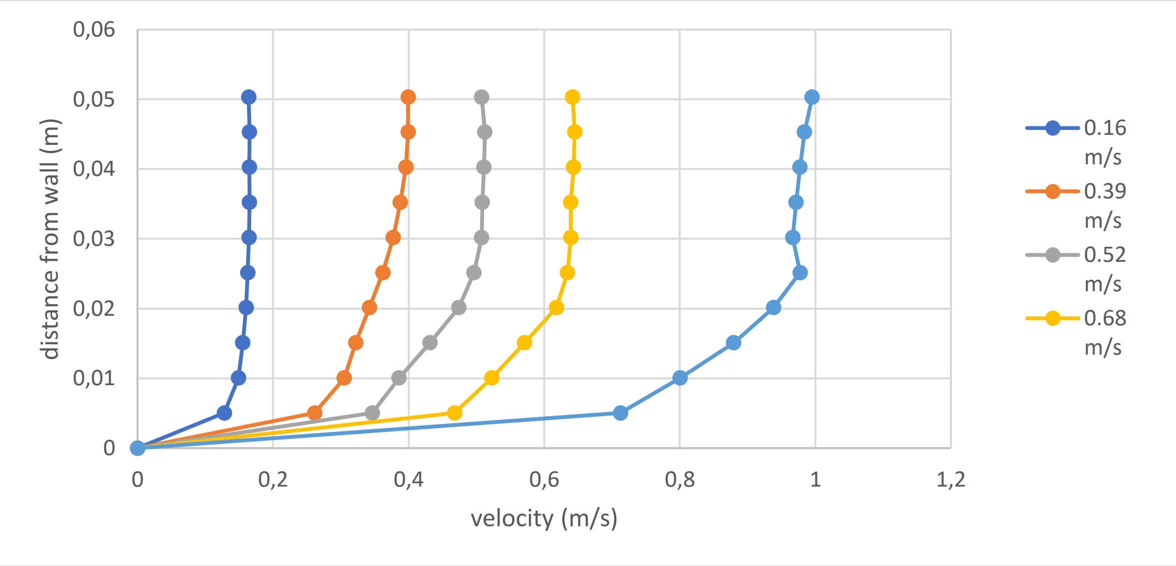

Figure 3: Flow tank measurements: Flow velocity profiles measured at 5 different velocities

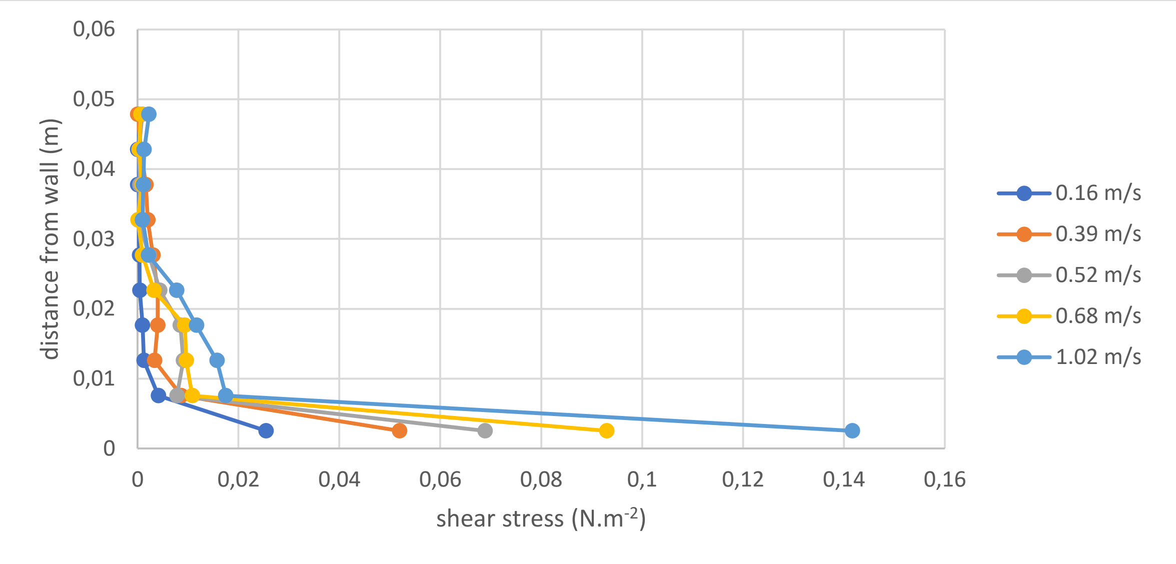

Figure 4: Flow tank measurements: Shear stress related to distance from the wall at 5 different flow velocities

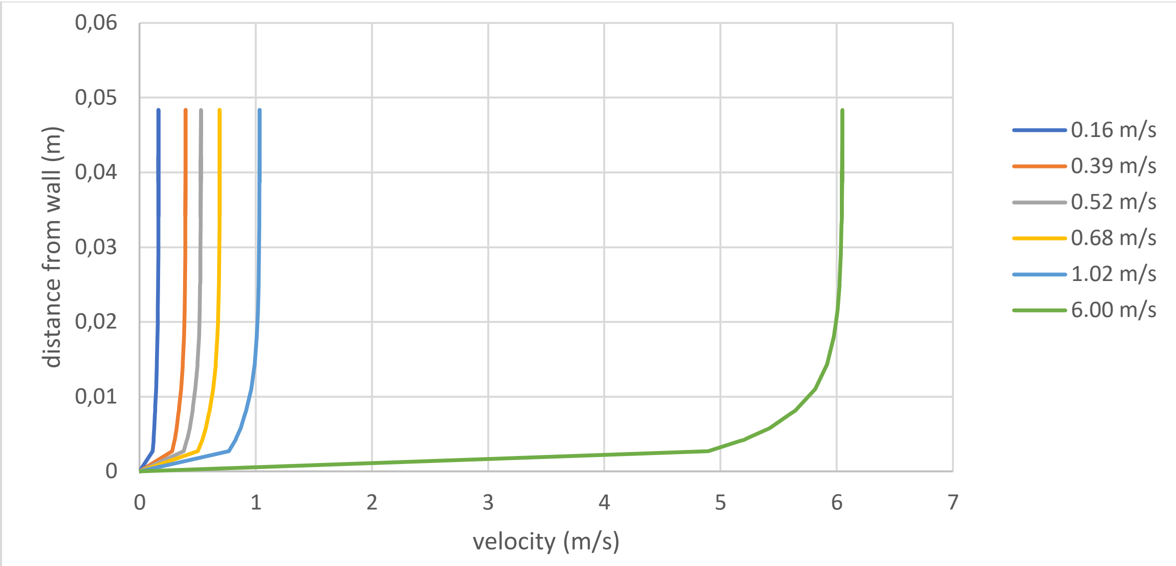

Figure 5: CFD-simulation (turbulent flow): modelled flow velocity profiles at 6 different flow velocities.

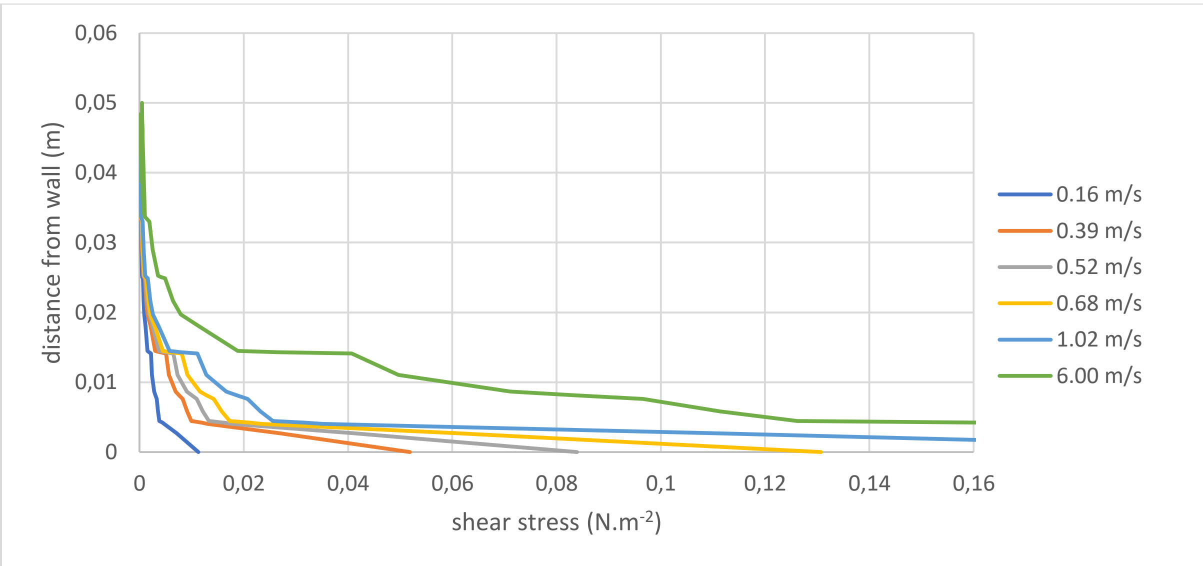

Figure 6: CFD-simulation (turbulent flow): modelled shear stress profiles at 6 different flow velocities.

Table 1: Measured and modelled Shear stress values at 1 cm from the kite and boundary layer thickness.

	Measured		Modelled	
Flow Velocity (m/s)	Shear stress at 1 cm ($N.m^{-2}$)	Boundary layer (m)	Shear stress at 1 cm ($N.m^{-2}$)	Boundary layer (m)
0.16	0.0013	0.025	0.0026	0.025
0.39	0.0034	0.040	0.0062	0.022
0.52	0.0091	0.030	0.0081	0.022
0.68	0.0097	0.025	0.0103	0.020
1.02	0.0158	0.025	0.0146	0.019
6	-	-	0.0586	0.018

3D flow phenomena and Shear stress levels due to passing by of the TidalKite:

During active deployment of the TidalKite, the edges of the frame beams and the wings of the system continuously create trailing vortices that interact with each other, generating a three-dimensional wake structure as indicated in Figure 7 (3D simulation, Weiler + Stamhuis, 2019). This wake pattern will of course decay in time, of which the effects are already visible in the Figure (left hand side).

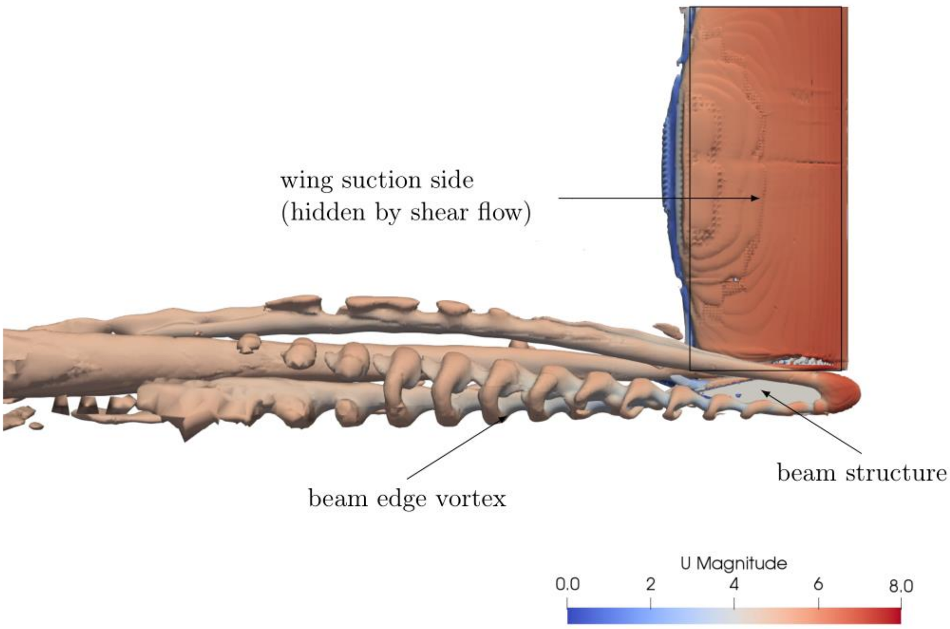

Figure 7: Wake patterns induced by the beam-wing interface of the TidalKite. Note that there is no significant vertical force generation, so no vertical downwash is observed. (NB: for orientation, the beam is oriented perpendicular to the page plane, the wing is upwards from the beam; the kite runs from left to right and we look from the position of the tether outwards).

The lift forces generated by the wings of the kite that are resulting from its action to harvest sea current energy, are predominantly developed in the horizontal plane (Weiler + Stamhuis, 2019) because the kite moves along horizontal lines through the water (see also Holtrup + Stamhuis, 2018). The hydrodynamic downwash resulting from the lift development is therefore not in the vertical direction, and will therefore hardly interact with the seafloor.

To get an impression of the disturbance of a TidalKite passing by, the shear stress values that are caused by the lower kite beam of the kite are analyzed against the vertical distance from the kite (see Figure 8). Maximum shear forces occur within very small vertical distance of the kite. As shown in Figure 8, shear stress forces at 25 cm of the lower kite beam are already smaller than 0.001 $N.m^{-2}$.

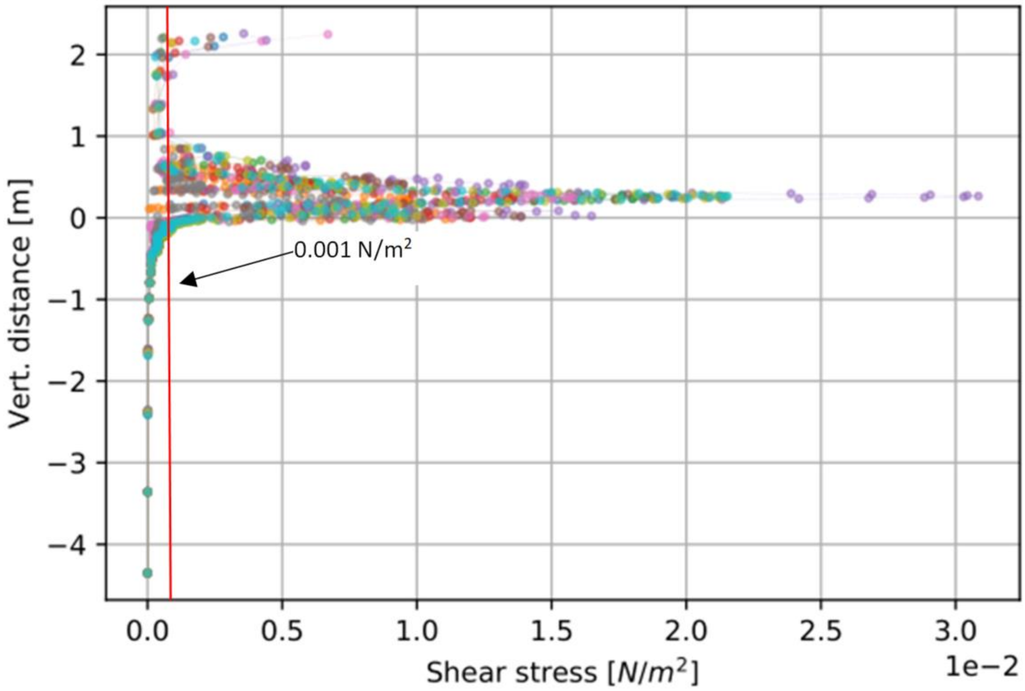

Figure 8: Shear stress calculated along a vertical axis passing through the kite wake, zero vertical distance is the position of the lower side of the lower kite beam.

Calculated shear forces were compared with critical bed-shear stress data from the literature (van Rijn, 2007). Critical bed-shear stress is defined as the shear stress value (in $N.m^{-2}$) at which erosion (i.e. movement of clay, silt or sand particles) of a certain sediment takes place. If the calculated shear stress as caused by the kite at the vertical position of the seafloor is higher than the critical bed-shear stress, disturbance of the seafloor is likely.

The critical bed-shear stress for a pure sand sample (200 µm) is about 0.2 to 0.4 $N.m^{-2}$ (van Rijn 2007). Critical bed-shear stress values for fine sediment (mud-sand) beds, as present in the Wadden Sea, may be lower due to the fact that the individual particles in these kinds of sediments are smaller. However, natural beds of fine sediments generally show cohesive effects due to the presence of cohesive (binding) forces between the particles.

Furthermore, the bed surface may become cemented due to mucus produced by diatoms and bacteria. Van Rijn reports critical bed-shear stresses in the range of 0.1 to 0.3 $N.m^{-2}$ for weakly consolidated mud beds. Others report values in the range of 0.05 to 0.5 $N.m^{-2}$ (Figure 9, reviewed by van Rijn 2007).

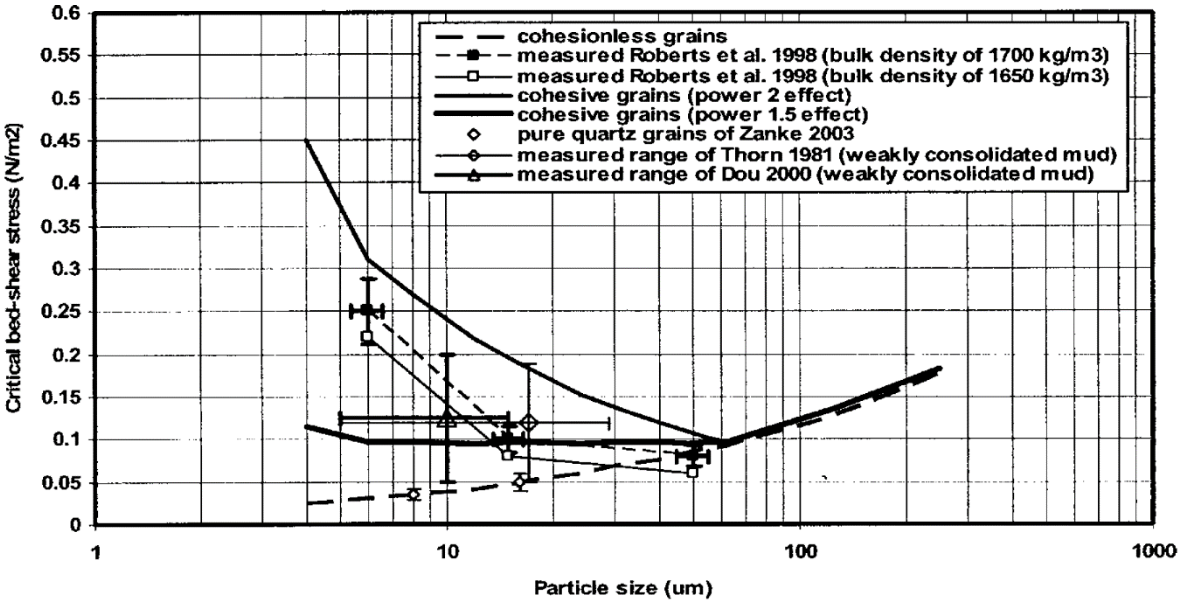

Fig 9: Overview of critical bed-shear stress for different sediments (van Rijn 2007).

Discussion and Conclusions

Measured and modelled shear forces caused by a moving kite appear to be very low at some distance from the actual kite. Already at 5 cm distance of the kite shear stress values are almost negligible. Also the downwash in vertical direction generated by a moving kite is very low because the wings work in a horizontal direction and therefore downwash does not/hardly interfere with the seafloor. As the TidalKite is buoyancy neutral, no dynamic lift is generated. This means that when the kite 'flies', and while there are significant hydrodynamic forces at work that accelerate the surrounding water, only very small forces act in the vertical direction and therefore the water acceleration in this axis is minimal. Calculated/simulated shear forces at 25 cm distance from the bottom of the kite are lower than 0.001 $N.m^{-2}$. This value is 50 times smaller than the lowest critical bed-shear stress value reported in literature (0.05 $N.m^{-2}$). This implies that if the kite is travelling horizontally even at a short distance above the seafloor (as small as less than half a meter), it will not disturb the seafloor at all. Only when it comes dangerously close to the seafloor, the shear caused by the flow deflections will disturb the seafloor but even then to a very limited level.

The velocity variability with depth according to EPRI (2006) shows that the water velocity near the seafloor is substantially lower than higher up in the water column. Other sources (Delft3D-Flow model assumptions, ADCP measurements performed by the UG and SeaQurrent) confirm this. This effect makes it undesirable (due to low energy availability) and impossible (due to an substantial difference between water flow energy for the lower wing row versus upper wing row) to operate the TidalKite near the seafloor, requiring at least 1 meter of distance. At such distances the level of bottom disturbance due to the TidalKite action is negligible i.e. not present.

In comparison, the impact of other tidal-stream energy extraction methods, such as an array of horizontal axis tidal turbines, on flow velocity field and bed-shear stress might be much higher (Gillebrand et al 2016). Since tidal turbines rely on strong tidal flows as present in small tidal channels, extraction of energy, i.e. strong local deceleration of the flow, can have significant impact on the residing current velocities, extending to several kilometers downstream.

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