Current reduction in AquaSim

TR-FOU-2500-1

Revision 2

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Summary:
This document describes how AquaSim calculates reduction of current on succeeding membrane panels for membrane type “Normal” and “Normal with bending stiffness”.

Two methods are available to apply in AquaSim:

- Lølands method: based on the report presented by (Løland, 1991).
- Energy method: the energy method is an assessment based on considering energy and the power of the system.

2	14.06.2024	AJB	ISH & HNM	Energy method implemented
1	04.11.2014	AJB	LFH	First revision
Revision no.	Date	Author	Verified by	Description

Content

1 Introduction

When current is passing nets, such as the ones applied in the aquaculture industry, the fluid velocity will be reduced behind the net. This means that nets behind other nets will experience less drag forces due to the reduced fluid velocity. Figure 1 show a simplified case with five nets spread out in the xz-plane, succeeding each other along the y-direction.

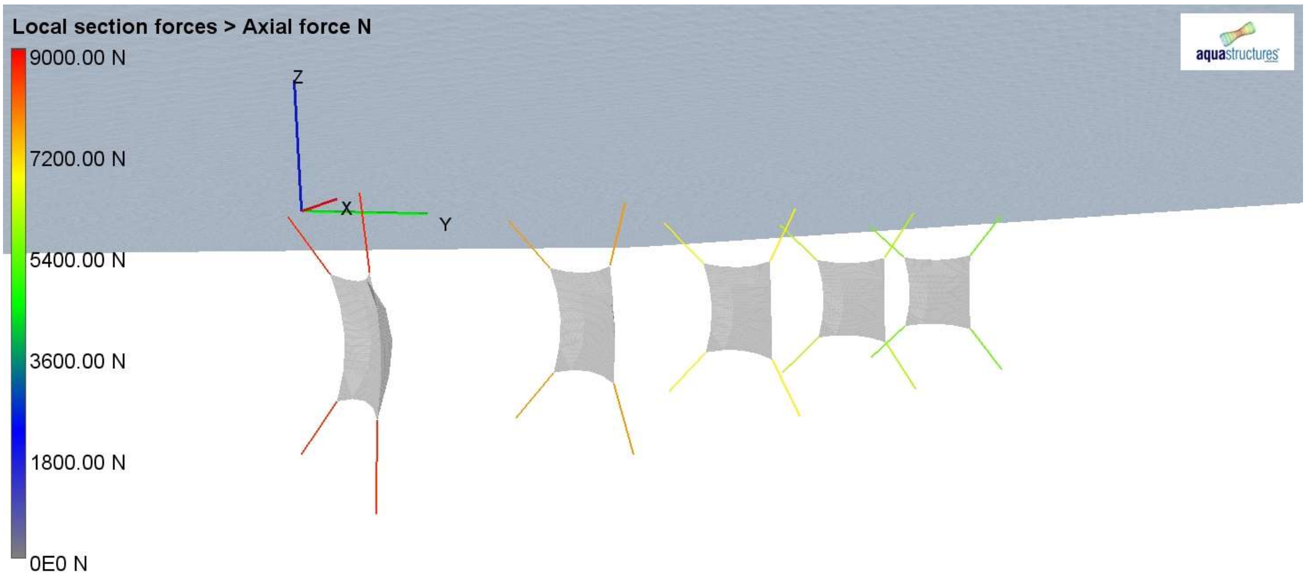


Figure 1 Fluid flow passing succeeding nets. The color indicates axial force in lines.

As seen from Figure 1, the forces in the lines attached to the nets becomes lower the further back along the y-direction one gets. The forces range from 9000 N on the upstream net to 5000 N on the one in the back.

This document presents a new method to account for flow reduction behind nets. The current state of art for accounting for current velocity reduction behind nets is the method presented by (Løland, 1991). This document also presents an alternative formulation to the reduction of flow velocity behind a net based on energy conservation. Theory, assumptions, and implementation to AquaSim are outlined in this document.

2 Theory

This section describes the theory for the two formulations that account for current reduction behind nets in AquaSim. The two methods are implemented for the membrane types “Normal” and “Normal with bending stiffness”. In this document, membrane type “Normal” and “Normal with bending stiffness” will be referred to as *net*.

2.1 Basics of nets

Consider a mesh shown in Figure 2.

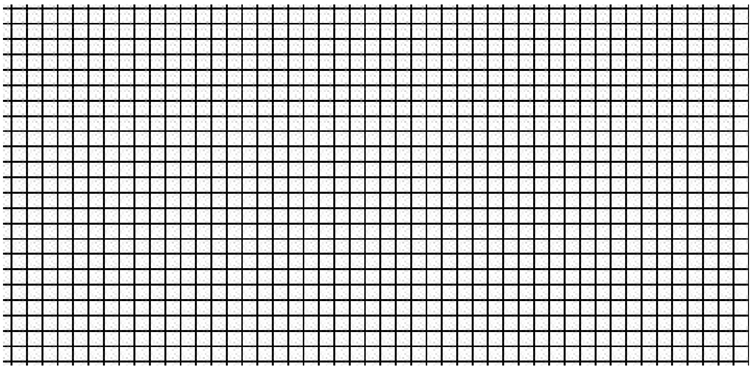


Figure 2 Mesh alternatively seen as a "screen".

If we zoom into Figure 2, it will resemble Figure 3 where local definitions are introduced.

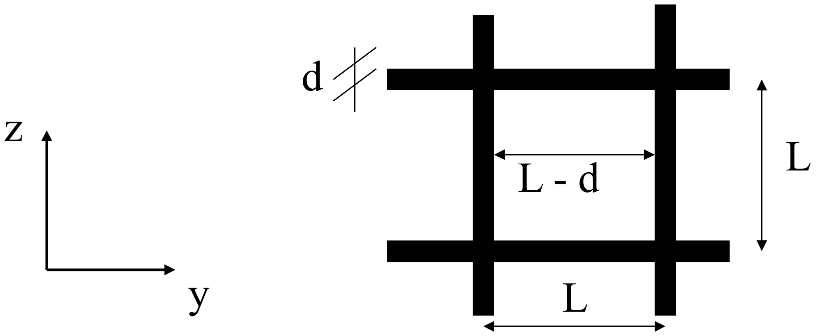


Figure 3 Definition to L and d of net twines.

Figure 3 is from (Berstad, Walaunet, & Heimstad, Loads from currents and waves on net structures, 2012) and

- L is the distance, center-center between adjacent twines.
- d is the diameter of each twine

The most common formal definition to Solidity (Sn) is $Sn = {}^{A_e}/_{A_{\square}}$, where A_e is the area casting shadow from a light perpendicular to the net and A is the total area of the net. For an ideal knotless mesh as shown in Figure 3 a mathematical expression for Sn can be formulated as:

$$Sn = \frac{d}{L_y} + \frac{d}{L_z} - \frac{2d^2}{L_y^2 + L_z^2}$$

Historically meshes were made with knots. This leads to higher solidity. A term having been used by e.g. (Løland, 1991) is:

$$Sn_{kn} = \frac{d}{L_y} + \frac{d}{L_z} + \frac{kd^2}{2\left(L_y^2 + L_z^2\right)}$$

where k is a constant, typically 1 or 2. Another simplified definition is found as:

$$Sn_{2D} = \frac{d}{L_y} + \frac{d}{L_z}$$

Equation 1

normally, we have that $L_y = L_z = L$ meaning that:

$$Sn_{2D} = \frac{2d}{L}$$

This is often denoted the “2D solidity” since it basically is based on summing diameters in both directions. This can be a good balance since most nets are not mathematically perfect with an example seen in Figure 4.

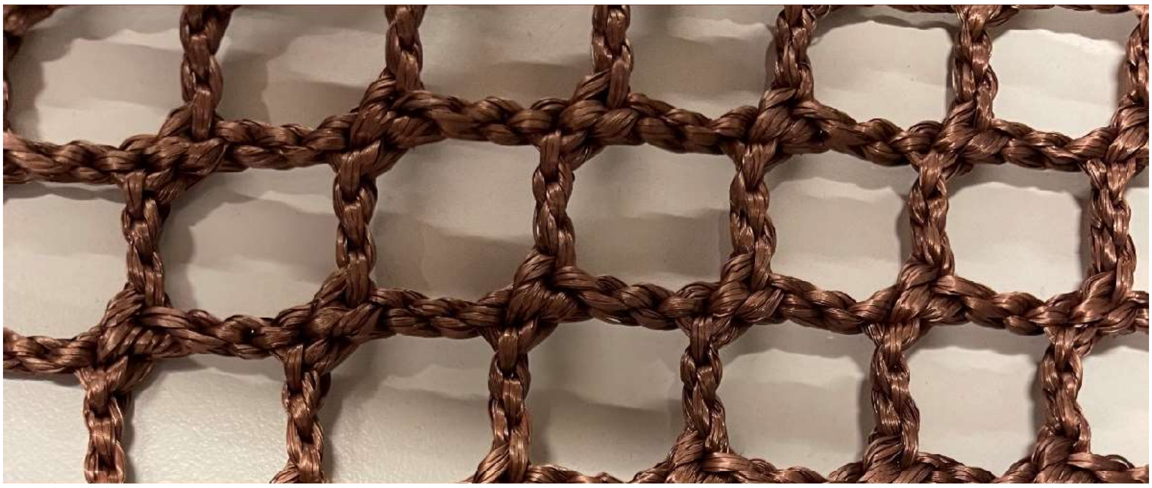


Figure 4 Net example.

2.2 Lølands method

The theoretical formulation for the current reduction According to Løland (1991) Eq. 211 is:

$$r_L = 1 - 0.46 \cdot Cd$$

Equation 2

where

- r_L is the current reduction factor, defined as ${}^{v_{red}}/_{v}$,
  - v_{red} is the current velocity behind the net,
  - v is the undisturbed current velocity,
- Cd is the drag coefficient of the net where the corresponding area is the full area of the net.

Meaning:

$$r_L = \frac{v_{red}}{v} = 1 - 0.46 \cdot Cd$$

Equation 3

Cd is found from (Løland, 1991) Eq. 199 as:

$$Cd = 0.04 + (-0.04 + 0.33Sn + 6.54Sn^2 - 4.88Sn^3) \cdot \cos\alpha$$

Equation 4

where Sn is the solidity and α is the angle of the net panel relative to the flow direction. To be consistent with (Løland, 1991), Sn is found from (Løland, 1991) Eq. 198 as:

$$Sn = \frac{2d}{L} + \frac{d^2}{2L^2}$$

Equation 5

where

- d is the diameter of each twine, according to Figure 3,
- L is the length of each twine, according to Figure 3.

2.3 The energy method

The energy method is an assessment based on considering energy and the power of the system. Consider a frame enclosing a permeable "screen" with current flowing through as shown in Figure 5.

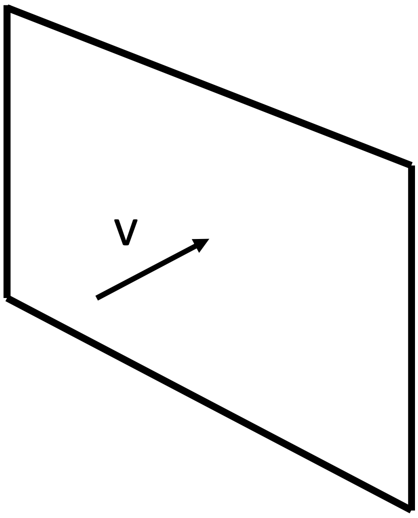


Figure 5 Screen with water flowing through having a cross section areal *A* to the flow.

The screen/frame in Figure 5 has area A.

By definition, the kinetic energy E of a moving mass, m with a velocity v is:

$$E = \frac{1}{2}mv^2$$

The mass of the fluid passing within an area A as in Figure 5 can be found as

$$m = \rho vtA$$

where

- ρ is the density of the water,
- t is the considered time period.

The means that the kinetic energy of undisturbed water passing through the area marked by the square in Figure 5 is:

$$E_{Flow} = \frac{1}{2}\rho tAv^3$$

Equation 6

The corresponding power, P (energy per time unit) is then:

$$P = \frac{1}{2}\rho Av^3$$

Consider a net being put into a flow field with an undisturbed velocity, v as seen in Figure 6. As energy must be conserved, the energy in Equation 6 represents the max energy to be either absorbed to the screen or passing through in the flow behind the net.

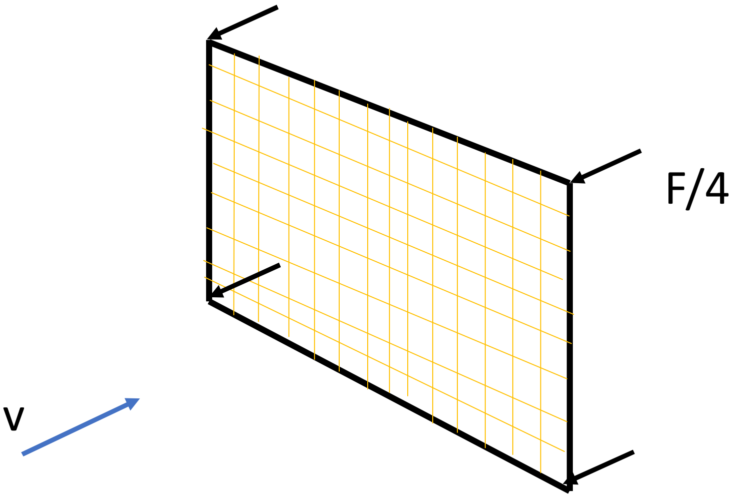


Figure 6 Net put into flow field.

The drag force to the net is by definition:

$$F_{drag} = \frac{1}{2}\rho CdAv^2$$

Equation 7

where Cd is the drag coefficient for the net based on the screen (i.e. membrane element) area A as representing the area. Now, let us follow in e.g. (Hansen, 2008) “1D momentum theory” where they consider flow about circular screen symmetric about a central axis in the flow direction as shown in Figure 7 where

- v is the undisturbed fluid flow upstream of the screen,
- u is the velocity at the screen,
- v_{red} is the reduced velocity behind the screen.

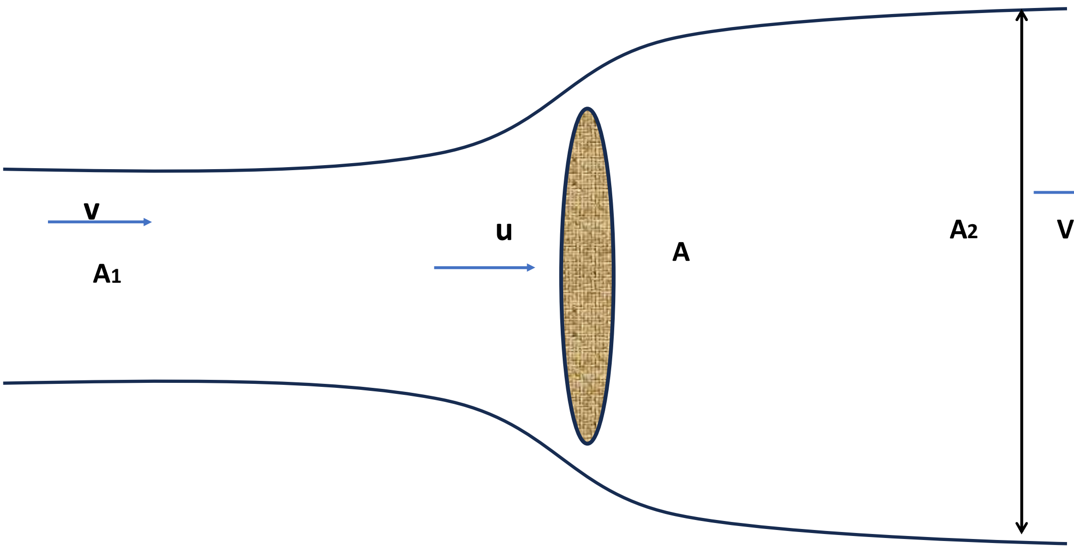


Figure 7 Flow through disc symmetric about the central axis.

The screen in Figure 7 will have a pressure drop over it, leading to a (drag) force pushing in the direction of the flow. For the vocabulary of Hansen, the drag force corresponds to the torque force, *T*. By putting up the applicable control volume (Hansen, 2008) ends up with e.g. Eq 4.12 and shows that the drag force to the disc in Figure 7 is:

$$T = F_{drag} = \rho u A(v - v_{red})$$

Equation 8

Where u is the flow velocity at the screen as illustrated in Figure 7. A is the total areal the screen covers cross sectional to the flow.

The flow velocity at the screen will be (Hansen, 2008) Eq. 4.11:

$$u = \frac{1}{2}(v + v_{red})$$

Equation 9

By inserting Equation 9 into Equation 8 it is seen that the drag force can be expressed as

$$F_{drag} = \frac{1}{2}\rho A(v + v_{red})(v - v_{red})$$

meaning

$$F_{drag} = \frac{1}{2}\rho A(v^2 - {v_{red}}^2)$$

Equation 10

Combining Equation 10 and Equation 7 means:

$$\frac{1}{2}\rho A(v^2 - {v_{red}}^2) = \frac{1}{2}\rho C d A v^2$$

Meaning

$$v^2 - {v_{red}}^2 = Cdv^2$$

Meaning

$${v_{red}}^2 = v^2(1 - Cd)$$

Meaning

$$v_{red} = v\sqrt{1 - Cd}$$

The fraction $\frac{v_{red}}{v}$ is then:

$$\frac{v_{red}}{v} = \sqrt{1 - Cd}$$

Equation 11

Denoting this fraction as r_E, we get:

$$r_E = \frac{v_{red}}{v} = \sqrt{1 - Cd}$$

Equation 12

Which in AquaSim then is the relation between the undisturbed flow v and the reduced flow velocity behind the net, v_{red}.

Following (Hansen, 2008) Eq. 4.16 an induction factor, *a,* can be defined, defining the relation between v and v_{red} where a is define by this relation:

$$v_{red} = (1 - 2a)v$$

This means

$$r_E = (1 - 2a) = \sqrt{1 - Cd}$$

Equation 13

According to Hansen Equation 12 is valid for a < 0.4 (Hansen, 2008) meaning that it is considered valid while $r_E > 0.2$ meaning it is valid for

$$Cd = 4a(1 - a) < 0.96$$

Assuming the drag coefficient is found as presented in Equation 20 in (Berstad, TR-FOU-100004-6 Revision 1, 2024):

$$Cd = \frac{Sn}{(1 - \frac{Sn}{2})^3}\left(1 - \frac{Sn}{4 + Sn}\right)^2$$

This then means that the current reduction is valid for a solidity of $Sn < 0.507$.

2.4 Comparison Løland and Energy method

2.4.1 Perpendicular flow

Consider a flow perpendicular to a net as shown in Figure 6. Calculate the relative velocity behind the net by Løland using Equation 2, and from the formal energy assessment using Equation 11. This is shown in Figure 8 where:

- r is the reduction factor, describing the ratio between the reduced velocity behind the net and the undisturbed velocity, $\frac{v_{red}}{v}$,
- r Energy, r_E are results from Equation 11,
- r Løland, r_L are results from Equation 2,
- The relative difference is the difference between the two reduction factors.

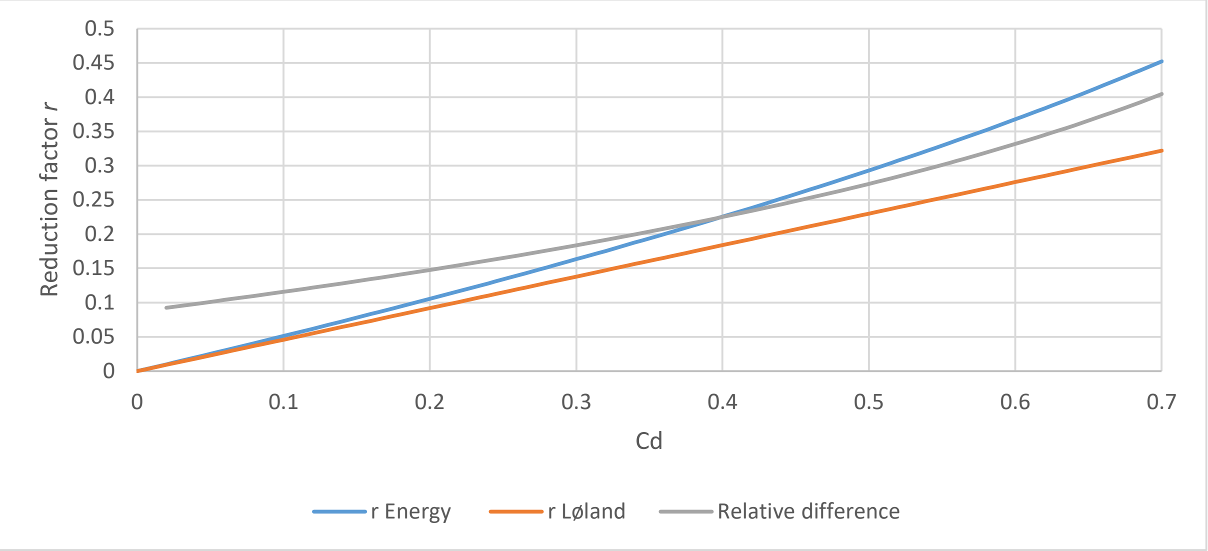


Figure 8 Flow velocity reduction behind net as function of Cd.

As seen from Figure 8 the energy method predicts more velocity reduction behind net than Løland method and the difference gets higher for higher Cd.

2.4.2 Flow at oblique angle

Consider inflow to a net with an angle as seen in Figure 9.

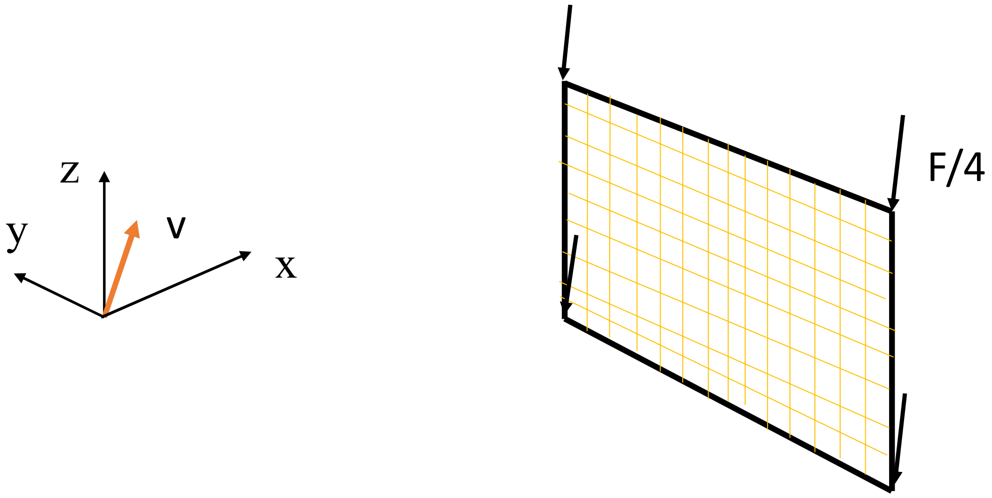


Figure 9 A net screen with flow at angle not perpendicular.

Per definition, the area used for calculating the force in Figure 8 is the area seen when looking in the direction of the flow. For oblique flow, this will correspond to a smaller area than the total screen area, as seen in Figure 10.

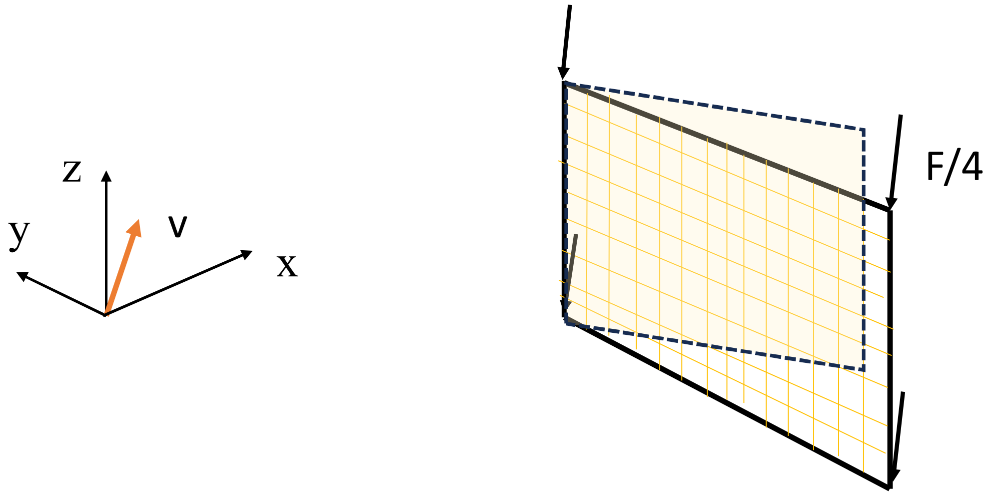


Figure 10 Net at oblique angle.

A net at oblique angle will give rise for both drag and lift forces and the flow behind will not be symmetric. However, in terms of energy the relation that extracted energy have a corresponding velocity reduction behind stands. This means:

$$F_{drag} = \frac{1}{2}\rho C d A_p v^2$$

Equation 14

Where A_p is the net area projected in the flow direction. This means we can find (by definition):

$$Cd = \frac{F_{drag}}{\frac{1}{2}\rho A_p v^2}$$

Equation 15

Or by including the energy loss due to lift, in addition:

$$Cd_E = \frac{F}{\frac{1}{2}\rho A_p v^2}$$

Equation 16

Where F is the total force acting by the current to the panel and Cd_E is factor to be used with Equation 12 to find the reduction factor behind the net as:

$$r_E = \frac{v_{red}}{v} = \sqrt{1 - Cd_E}$$

Equation 17

A panel been analyzed for a case with a 2D solidity of 20%. Figure 11 presents the reduction factor, by applying Equation 16 and then Equation 17 to find the reduction factor r Energy, r_E. In Figure 11 this is compared to the reduction factor predicted by Løland, r_L.

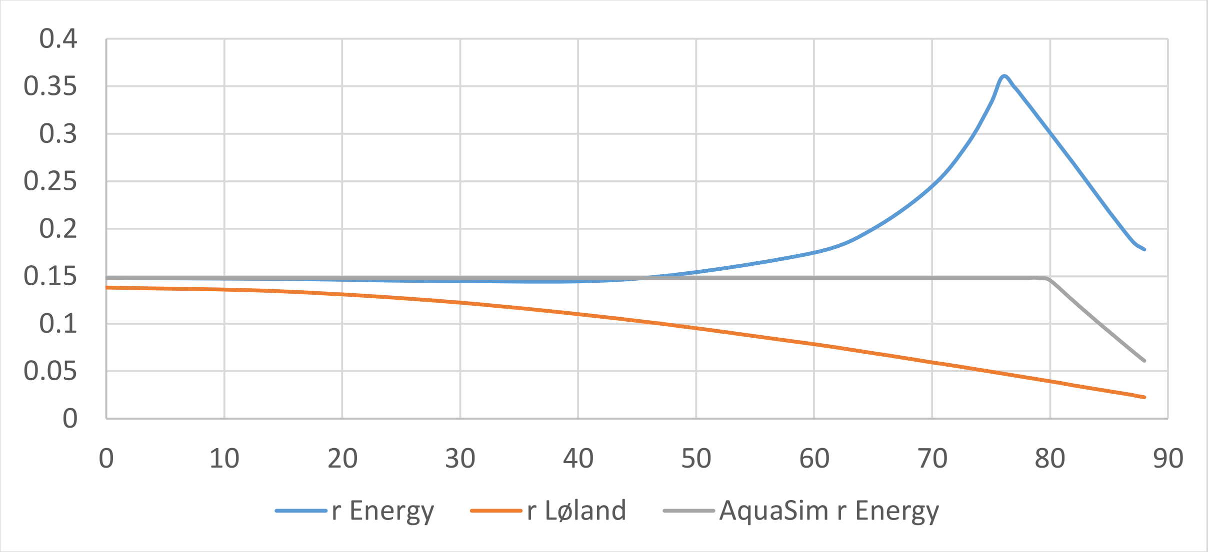


Figure 11 Velocity reduction factors (1-r) as a function of inflow angle.

As seen from Figure 11 the velocity reduction varies differently based on the two approaches. For the Løland approach, the most part of Cd decays with the angle such that the reduction of velocity decreases with increasing angle. As one can imagine, this will not be the case for a real panel based in the energy approach since the skewing the net means more twines in a smaller projected area. The line "*r Energy*" in Figure 11 is derived by calculating the force to the panel and divide by the projected area of the panel perpendicular to the flow. Oblique flow will lead to different loading to twines due to the fact that the inflow is not perpendicular as illustrated in Figure 12.

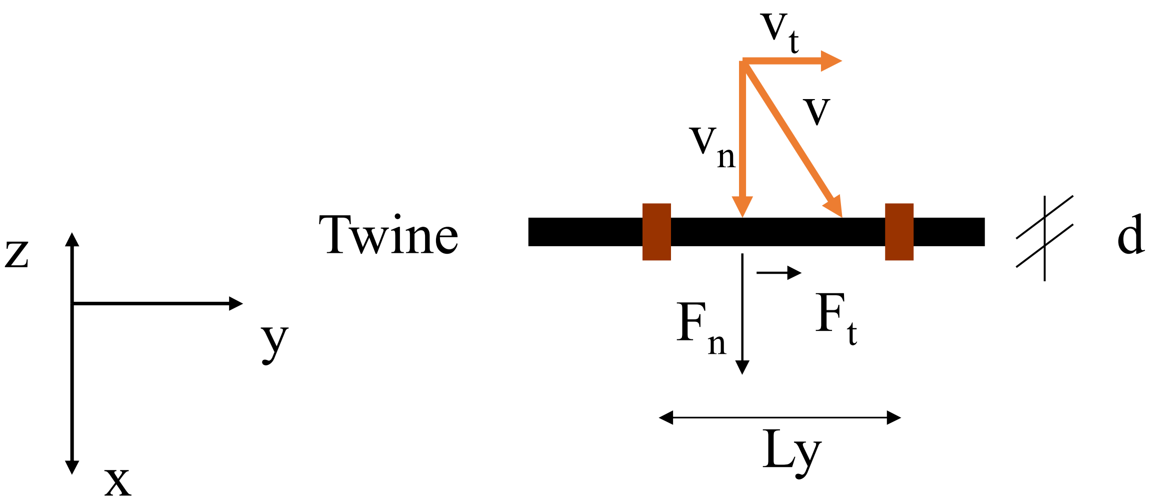


Figure 12 Local flow angle.

In AquaSim the drag force to an element is assumed reduced to an element from succeeding twines as one is closing in on tangential flow as illustrated in Figure 13. This means that when the flow becomes more parallel to an element the force decreases from this.

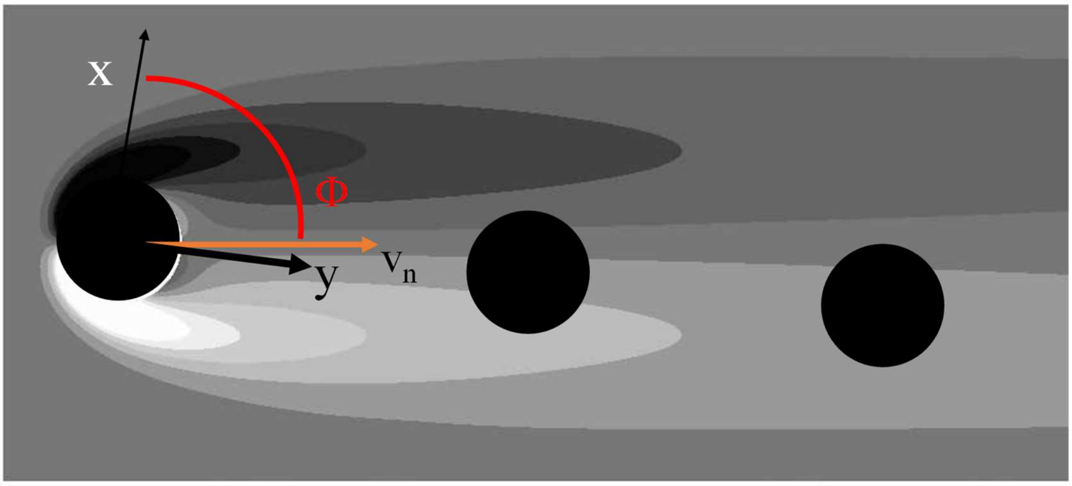


Figure 13 Succeeding twines partly shaded from incident flow. (Barkley, 2006).

Based on the calculation of drag force in AquaSim, the resulting force will lead to the relation seen in Figure 11. If it had not been for the effect shown in Figure 13 accounted for in the drag force calculation, the reduction would have been going further upward towards 90 degrees and not bend downwards at approximately 75 degrees. These effects are elaborated more in detail in (Berstad, Walaunet, & Heimstad, Loads from currents and waves on net structures, 2012).

For analysis, the more the flow is reduced, the less conservatism is included into forces on the succeeding nets. In order to keep simplicity and conservatism, but still be more accurate than Lølands formula, the line “AquaSim r Energy” from Figure 11 is introduced to AquaSim to account for flow reduction behind nets.

3 Implementation of reduction factor.

The velocity reduction based in an energy consideration is implemented to AquaSim as shown in Figure 14.

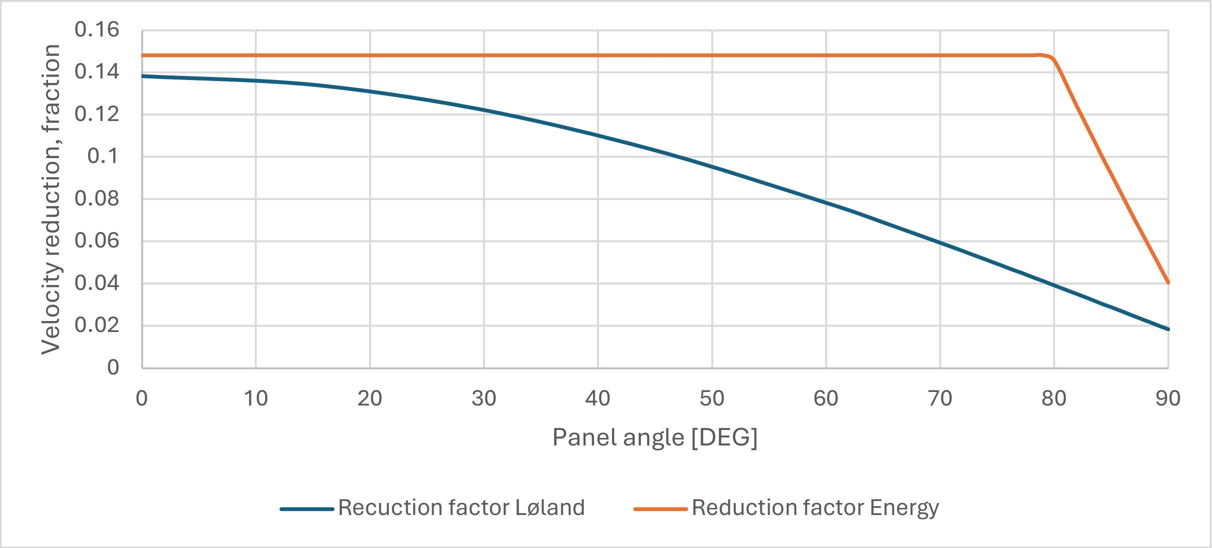


Figure 14 Current reduction Løland method vs Energy method

As seen from comparing Figure 14 to Figure 13 it is seen that the implemented reduction from the energy method has been reduced a bit from the analytical results in the area from 45 DEG and up to 90 DEG. Since the energy method gives a larger reduction than Lølands method it is chosen to use the 0 degree reduction factor up to 80 degrees and then reduce it such that:

$$r_E = \sqrt{1 - Cd_{use}}$$

Equation 18

$$Cd_{use} = Cd_{E0} * min(1, 4\cos(\alpha) + 0.04/Cd_{E0})$$

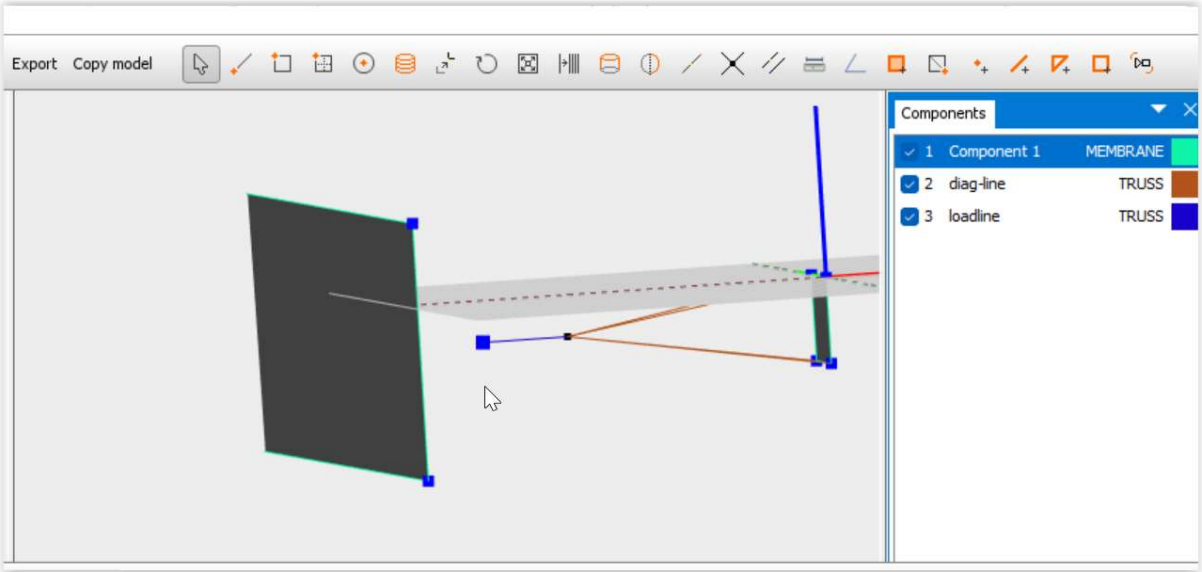
Equation 19

Where Cd_{E0} means Cd_E at *0* degrees.

3.1 Case study

3.1.1 Analysis model

Figure 15 shows a case where a net is sheltered behind a net.



☑	1	Component 1	MEMBRANE	🟩
☑	2	diag-line	TRUSS	🟫
☑	3	loadline	TRUSS	🟦

Figure 15 Case study. Net behind screen.

The screen and the net have the same net data given in Table 1.

Table 1 Net data.

Net data	
Net area [m2]	100
Net 2D solidity	0.2
Screen 2D solidity	0.2
Cd_{cyl}	1
Cd_{mem}	1.37
Cd	0.27
Unsheltered force [kN]	14.06

3.1.2 Analysis response

Figure 16 and Figure 17 shows response at an oblique angle.

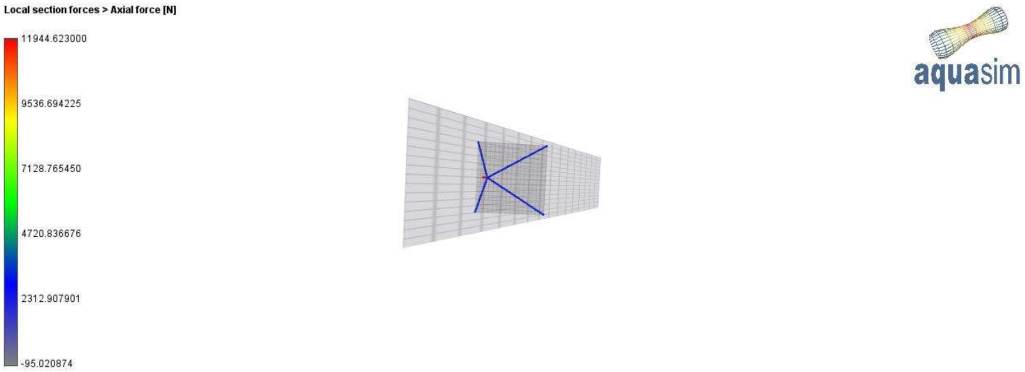


Figure 16 Response at oblique current direction through screen.

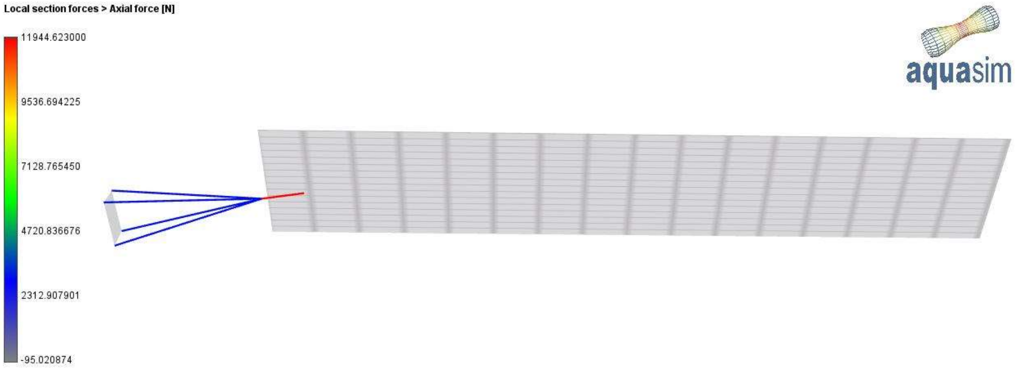
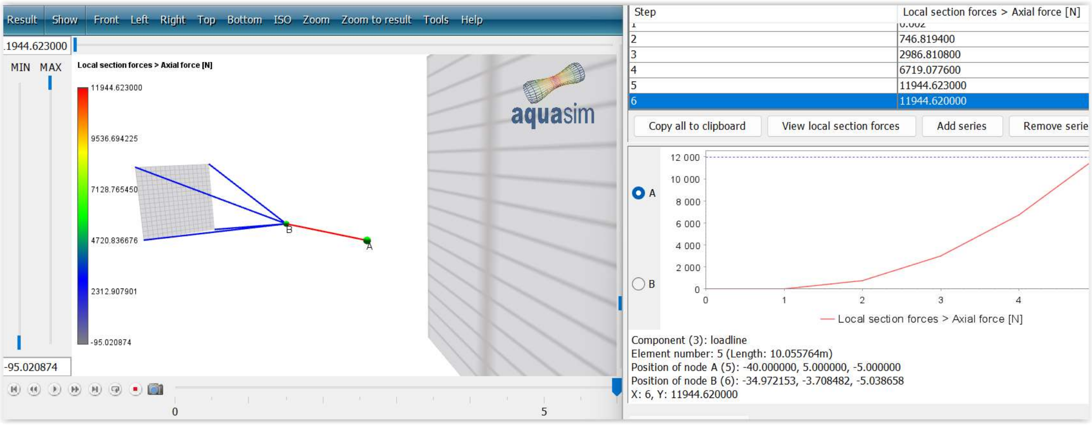


Figure 17 Response at oblique current direction through screen seen from another angle.

As seen from Figure 16 and Figure 17 the sheltered net it withheld with bridles and a rope such that it aligns with the current direction. The current direction is then adjusted with different angles such that the formulas for current reduction by Ølands method and the energy method (Equation 18 and Equation 19) can be compared at varying flow angles through the screen. Results are extracted as axial force in the line as seen in Figure 18.



Step	Local section forces > Axial force [N]
1	0.002
2	746.819400
3	2986.810800
4	6719.077600
5	11944.623000
6	11944.620000

Component (3): loadline
Element number: 5 (Length: 10.055764m)
Position of node A (5): -40.000000, 5.000000, -5.000000
Position of node B (6): -34.972153, -3.708482, -5.038658
X: 6, Y: 11944.620000

Figure 18 line where forces are extracted.

3.1.3 Analysis results

Results are shown in Figure 19.

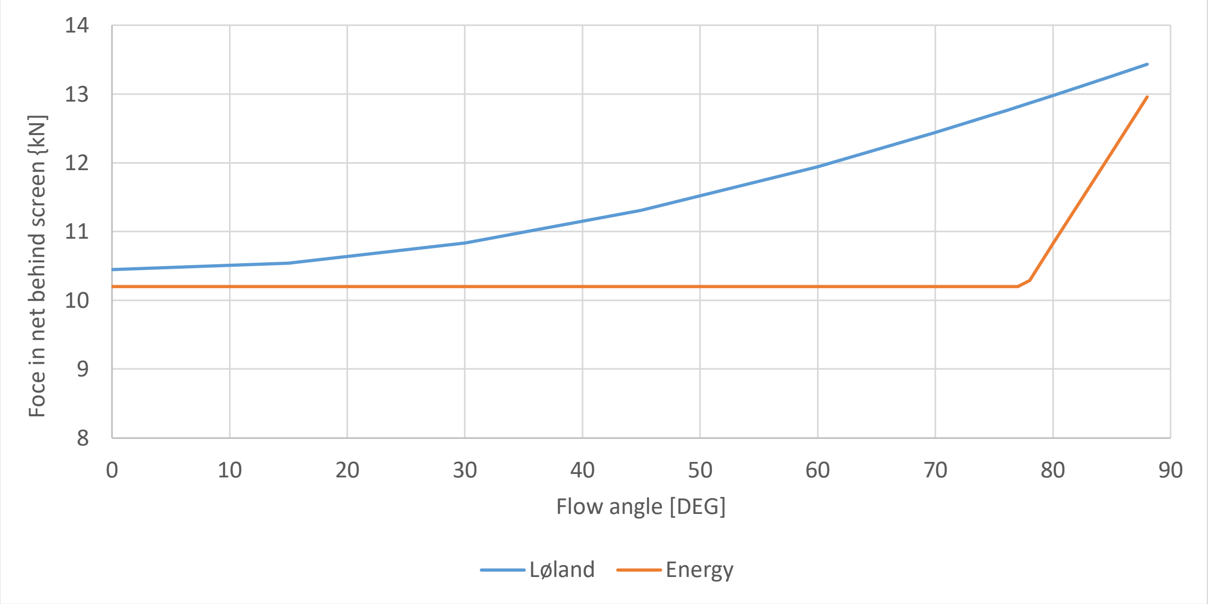


Figure 19 Force in truss seen in Figure 18.

As see from Figure 19 the energy method means lower forces in the net behind the screen due to the fact that the energy method leads to a slightly larger current reduction of the flow passing through the screen, compared to Løland.

4 References

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