Bowthrusters and the stability of a riprap revetment

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Abstract

Because of problems with the design guidelines produced by PIANC for armoured slopes under attack by bowthrusters, additional work has been done in the Netherlands. On the basis of this work computational rules have been developed. However, because of the increase of bowthruster power, more detailed knowledge is needed on the effect of a bowthruster on the stability of a riprap revetment. Especially large, fast vessels will cause problems to shore protection. Recently P&O put into operation the "Pride of Rotterdam", a luxury ferry with two bowthrusters with a capacity of 2000 kW each. When the captain uses both thrusters simultaneously, there is a considerable risk of damaging the rock of the underwater slope protection. But also with relatively small vessels for inland navigation problems arise when skippers use their bowthrusters.

For the calculation of the effect of a bowthruster at this moment the common methodology is to use the hydraulics of a plain jet. This is not correct because the propeller in the tube causes quite some extra turbulence. This extra turbulence will cause extra damage to the shoreline protection. So in a good design formula for the determination of stability in a bowthruster-flow, he effect of additional turbulence of the propeller has to be included.

Nomenclature

b	m	width of the mixing zone
C	$m^{1/2}/s$	Chézy roughness parameter
d	m	propeller diameter
d_{50}	m	median rock diameter
g	m/s^2	acceleration of gravity
h	m	waterdepth
k_r	m	Nikuradse roughness parameter
P	W	power of the engine
r	m	radial distance from the centre line of the jet
r_u	-	relative turbulence intensity
$\bar{u}$	m/s	depth averaged velocity

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u_m	m/s	maximum velocity in a certain cross-section
u_b	m/s	velocity at the bottom
$u_{b\text{-}max}$	m/s	maximum velocity at the bottom
u_i	m/s	velocity in the Izbash equation
u_0	m/s	outflow velocity, velocity when the water leaves the propeller jet tube
u_*	m/s	shear velocity according to Shields
u'	m/s	turbulent velocity fluctuation
v_s	m/s	ship velocity
x	m	horizontal distance
z	m	vertical distance (from the bed)
z_b	m	vertical distance between the propeller and the bed
z_0	m	theoretical point where the log-velocity profile assumes zero velocity
α	-	slope angle
Δ	-	relative density of rock (= $(\rho_s-\rho_w)/\rho_w$)
κ	-	Von Kármán constant (≈0.38)
ρ_s	kg/m^3	density of bed material
ρ_w	kg/m^3	density of water
τ	N/m^2	Shear stress
φ	-	angle of repose
ψ	-	Shields number

Introduction

For positioning a ship near a mooring facility nowadays more and more a bowthruster is used.

A bowthruster is a propeller placed in or under the bow, in order to generate a force perpendicular on the axis of the ship, in order to allow turning at very low speed. For some small yachts such bowthrusters can be lowered from the hull during manoeuvring. In other ships the bowthruster is placed in a small pipe going through the hull of the ship near the bow. In large ships such bowthrusters can have considerable sizes. The propeller race from such a bowthruster has a considerable impact on the revetment. For the calculation of the effect of a bowthruster at this moment the common methodology is to use the hydraulics of a plain jet. Most probably this is not correct. The propeller in the tube causes quite some extra turbulence. This extra turbulence will cause extra damage to the shoreline protection. So in a good design formula for the determination of the effect of a bowthruster, the effect of the propeller has to be included.

At this moment the problem of stability of riprap under attack by bowthrusters has become very relevant for two reasons. Recent generations of large ferries have extremely powerful bowthrusters to fasten the mooring procedures. Especially large, fast vessels will cause problems to shore protection. Recently P&O put into operation the “Pride of Rotterdam”, a luxury ferry with two bowthrusters with a capacity of

2000 kW each. When the captain uses both thrusters simultaneously, there is a considerable risk of damaging the rock of the underwater slope protection.

But also ships used in inland navigation are using bowthrusters more intensively. Because of high costs of crew, many inland navigation ships try to sail with a minimum of crew. In order to allow mooring with a limited number of staff, the manoeuvrability of the ship has to be improved, which is often done by making a bowthruster in the ship. At this moment near mooring dolphins near the locks in the navigable rivers of the Netherlands we are confronted with damage to the slope protection because of heavy use of bowthrusters

In order to investigate the problem of additional turbulence some laboratory tests have been performed, focussing on three cases:

- The effect of a plain jet
- The effect of a propeller in a tube
- The effect of a propeller without tube.

For these three cases the stability of rock is compared for a given slope, a given rock size (distribution) and a given position of the bowthruster.

From these the conclusion can be drawn that it is necessary to improve design formulas for the effect of a bowthruster. The second step is then to make a conceptual model of the effect of (propeller-induced) turbulence on the stability of the slope, followed by a systematic set of tests in the lab in order to verify the conceptual model and in order to determine the calibration constants in the conceptual model.

The PIANC Guidelines

In 1997 PIANC has published the “guidelines for the design of armoured slopes under open pile quay walls” [PIANC 1977]. In these guidelines a very rough method is described for the determination of the size of rock on slopes under attack by propeller induced currents. Basically the method is as follows:

1. Determine the power and the diameter of the bowthruster of the design ship.
2. Given these values, determine the initial jet velocity flowing out of the bowthruster (u_0).
3. Determine the height of the bowthruster above the bed (z_b).
4. Determine the ratio u_0/u_m from a presented graph
5. When the slope is in a zone $4\ z_b < x < 10\ z_b$ use the found velocity u_m.
6. Read the required stone size from a graph, and increase the value with 50% because you are on a slope.

In fact this method is not very reliable, and subject to much discussion. Especially because the determination and stability calculation can be done with much more accuracy.

Analysis of the flow

The flow behind a ship's propeller is very similar to flow in a circular jet, so it can be expected that the same proportionalities are valid. This is not necessarily the case for the numerical values, since there are also differences. For example, the water in the jet is already turbulent because of the propeller blades; this will make the flow establishment region shorter than in a free jet. Another difference is the water surface, which will influence the divergence of the jet. The following analysis of the flow is mainly based on SCHIERECK [2001] .

Figure 1 shows the turbulent velocity fluctuations in a free circular jet, compared with the fluctuations in a propeller wash. The relative fluctuations in the fully developed jet lie around 30% for both jets, but with the propeller this value is reached much earlier. It can therefore be expected that the propeller jet will diverge more than a free jet.

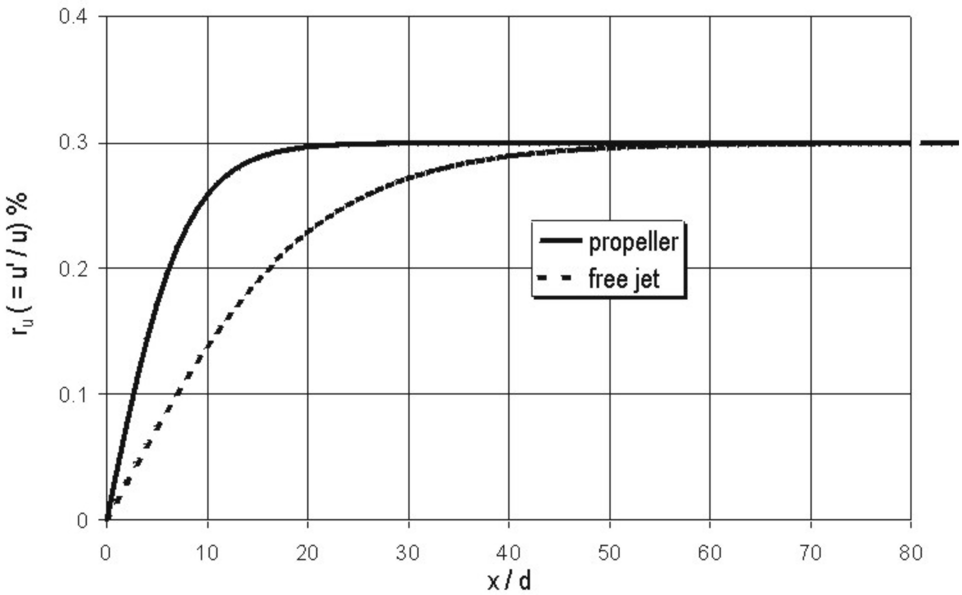

Figure 2 Turbulence in propeller wash and free circular jet (from RIJKSWATERSTAAT/DHL [1988])

The jet properties can be described with expressions analogous to the relations for free jets as described by RAJARATNAM [1976]. The velocity distribution can be described as a Guassian curve with only two parameters, u_m (u in the centre of the jet) and b (a typical width, usually defined where $u = u_m/2$):

$$\left.\begin{aligned} u_m &= \frac{2.8u_0}{x/d} \\ b &= 0.21x \\ u &= u_m e^{-0.69\left(\frac{r}{b}\right)^2} \end{aligned}\right\} \quad u = \frac{2.8u_0}{x/d} e^{-15.7\left(\frac{r}{x}\right)^2} \tag{1.1}$$

These expressions and Figure 3 show that a propeller jet indeed diverges faster than a free circular jet. The width, b, is about twice the value in a free circular jet.

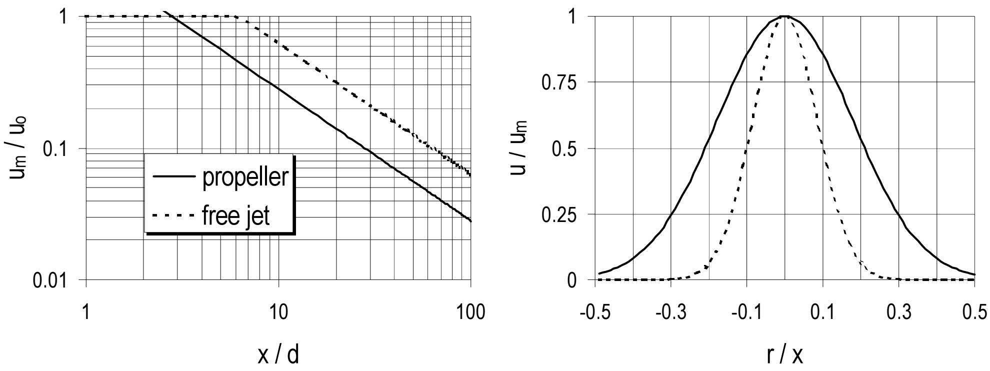

Figure 3 Velocity distributions in propeller wash and free jets

The values in these formulae can be estimated with: d = 0.7·diameter for a normal propeller and d = diameter for a propeller in a jet tube. When the diameter of the propeller is not known, it can be estimated at about 70% of the ship's draught when unloaded, but usually such data is available. The outflow velocity u_0 can be estimated with:

$$u_0 = 1.15 \left(\frac{P}{\rho_w d^2} \right)^{1/3} \tag{1.2}$$

where P is the power of the engine (in W).

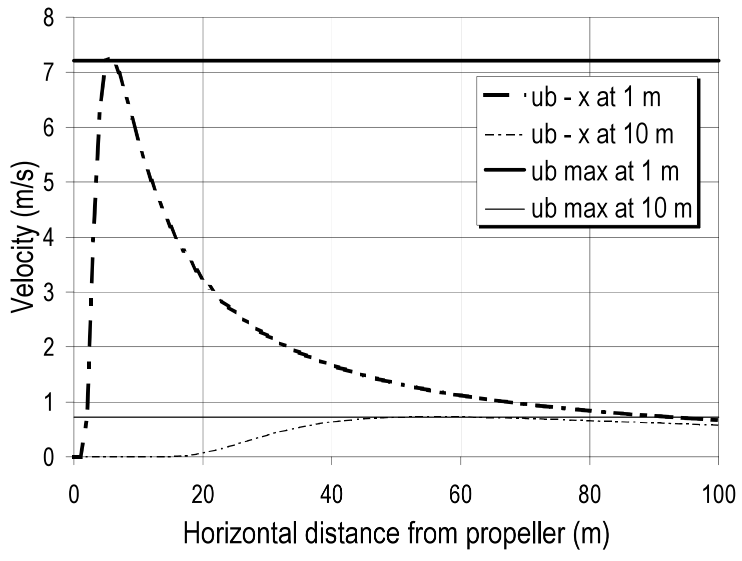

Figure 4 Velocities behind propeller for various cases

When the location of the maximum or the distribution of the velocity on the bottom is not important, the maximum velocity on the bottom can be determined by differentiating equation (1.1) to x. This gives x = 5.6 r for the location of the maximum velocity. This value in equation (1.1) gives:

$$u_{b-\max} = 0.3 u_0 \frac{d}{z_b} \tag{1.3}$$

where z_b (= r in equation (1.1))is the vertical distance between the propeller axis and the bottom.

Figure 3 shows the relation between equation (1.1) and equation (1.3) for distances of 1 m and 10 m below a propeller of 1 m diameter and an engine power of 10^7 Watt.

The velocities behind a ship's propeller are important in case the revetment or the bottom can be attacked by this flow when the ship is stationary or is manoeuvring near the bank. Once the ship is moving, this load becomes less important as the velocities in the jet are compensated by the speed of the ship (in the ideal case the ship has a velocity equal to u_0 while the jet remains motionless; compare a rocket at full speed). In that case, an indication of the velocity at the bottom can be found by reducing the values for u found with equation (1.3) with the speed of the ship. RIJKSWATERSTAAT/DHL [1988] recommends reduction with half the speed of the ship, which can be seen as a conservative design approach:

$$u_b = u_{b-\max} - 0.5 \quad v_s \tag{1.4}$$

Relation between Shields and Izbash

Izbash found that there is a relation between the velocity "near the bed" and the moment of incipient motion of grains, which he expressed as:

$$\Delta d_{50} = A \frac{u_i^2}{2g} \tag{1.5}$$

in which u_i is the velocity "near the bed" and **A** an unknown coefficient. Curve fitting resulted in a value of A = 0.7. In fact, Izbash did not derive this relation on a very fundamental basis.

Shields tried to derive such a relation in a more fundamental way, by setting up a balance of forces. He equated the loss of momentum (to be measured by head-loss) to the force exerted by the bed on the flow. The Chézy-equation gives a relation between the mean velocity and a head-loss (gradient). In order to determine the tractive forces, he had to apply a velocity profile. He adapted the logprofile:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{1.6}$$

in which z is the co-ordinate measured from the bed, κ the constant of Von Kármán, z_0 is height where the theoretical velocity becomes zero and u_* is a constant to be determined later. It is found that:

$$z_0 = k_r / 33 \tag{1.7}$$

in which k_r is the Nikuradse roughness parameter. This parameter depends on the d_{50} of the grains, but is usually more (because the bed does not consist of one single layer of marbles glued to the bed:

smooth bed $k_r = 2\ d_{50}$
Boutovski $k_r = 6\ d_{50}$
Van Rijn $k_r = 4 - 5\ d_{50}$

In fact u_* represents the force exerted by the bed on the flow. However, in equation (1.6) u_* needs to have the dimension of velocity. The relation between the tractive force and the parameter u_* is given as:

$$u_* = \sqrt{\frac{\tau}{\rho_w}} = \frac{\sqrt{g}}{C}\bar{u} \tag{1.8}$$

and

$$C = \frac{\sqrt{g}}{\kappa}\ln\left(\frac{12h}{k_r}\right) \tag{1.9}$$

Based on the above considerations, Shields came to his relation:

$$\Delta d_{50} = \frac{\bar{u}^2}{\Psi C^2} \tag{1.10}$$

in which Ψ is the constant of Shields.

So, in fact we have two equations to calculate the incipient motion, the Shields equation, using the mean velocity as input and the Izbash equation using a velocity u_i at an unknown level. Shields has explicitly used a logarithmic velocity profile, while Izbash did not define his profile. Of course, the formula of Izbash is also valid in case of a logarithmic velocity profile, provided the velocity is measured at the right level. So a relevant question is where to measure the velocity when applying the Izbash formula.
This can be found by equating the Shields and the Izbash formula:

$$\frac{\bar{u}^2}{\Psi C^2} = 0.7\frac{u_i^2}{2g} \tag{1.11}$$

or:

$$u_i = \sqrt{\frac{2g}{0.7}\frac{1}{\Psi C^2}}\,\bar{u} \tag{1.12}$$

Combining this with (1.8) leads to:

$$u_i = \sqrt{\frac{2}{0.7\Psi}}\,u_*$$

Observations have shown that in usually all cases the mean velocity is measured on 40% of the waterdepth, measured from the bed, so:

$$\bar{u} = u(0.4h) = \frac{u_*}{\kappa}\ln\left(\frac{0.4h}{z_0}\right) \tag{1.13}$$

For a practical situation this may lead to the following:
Suppose we have a waterdepth of 10 m and a stone-size of approximately 5 cm. This stone is dumped, so the value of k_r is 5 times 5 cm is 25 cm. We will use a $\bar{u}$ of 1 m/s.

With equation (1.9) (and using g = 9.8 and κ = 0.38) this leads to C = 50 $m^{1/2}$/s and u_* = 0.062 $\bar{u}$ = 0.062 m/s. Applying (1.6) for u=u_* gives that $z(u_*)$ = 1.46 z_0 and for u_i it gives u_i= 10 u_*. This is illustrated in Figure 5.

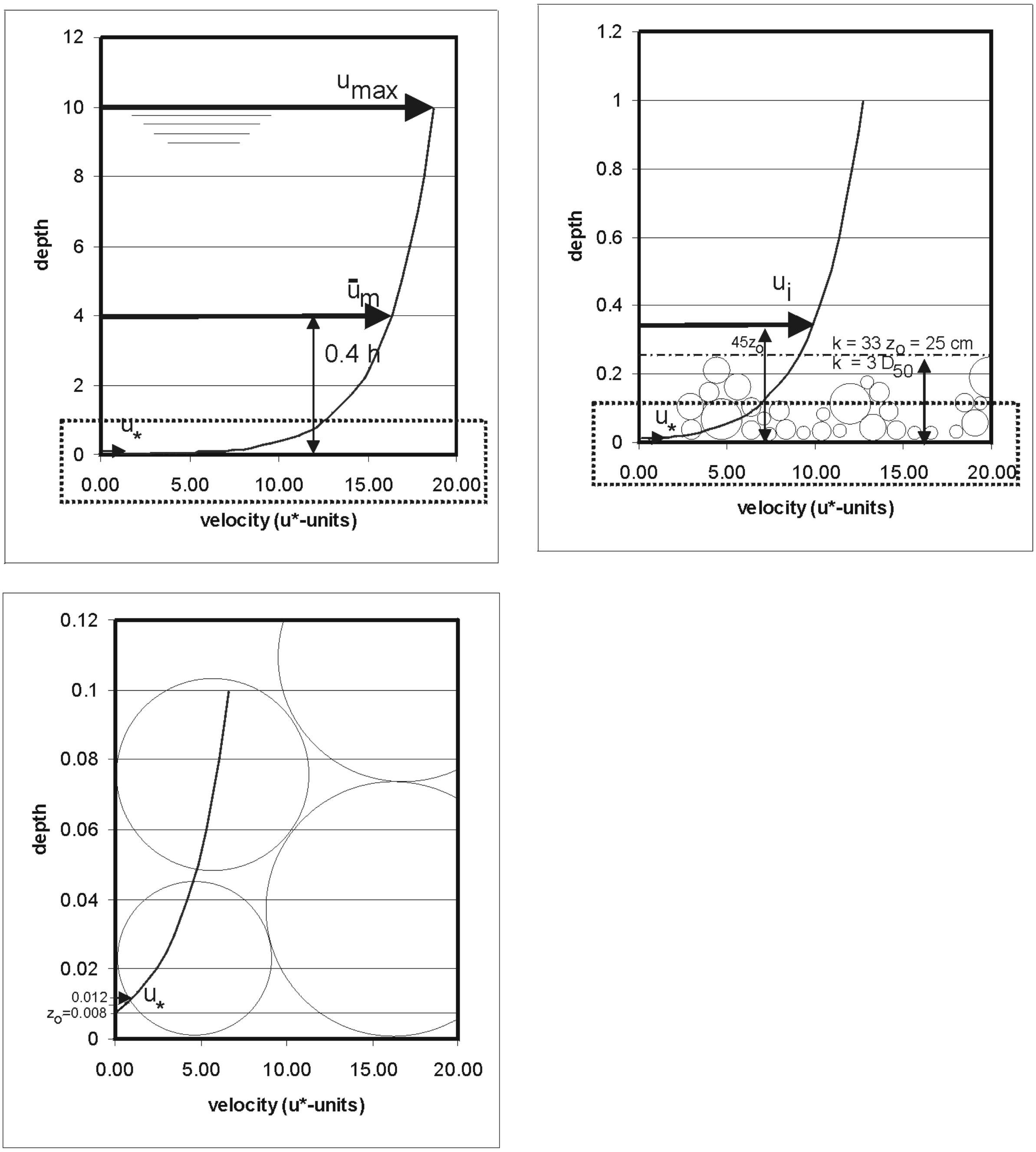

Figure 5: velocity profile on different scales

Turbulence effects

So one can recalculate the Izbash equation into the Shields equation and vice-versa. Both in the Shields equation as well as in the Izbash equation a certain degree of turbulence is assumed.. As is known, the real velocity can be written as:

$$u = \bar{u} + u' \tag{1.14}$$

In this equation *u'* is the turbulent fluctuation. Because stability does not depend on the *u* itself, but on u^2, in fact one should use:

$$u^2 = (\overline{u} + u')^2 = \overline{u}^2 + 2\overline{u}u' + u'^2 \tag{1.15}$$

This has to be time-averaged, which leads to:

$$\overline{u^2} = \overline{\overline{u}^2 + 2\overline{u}u' + u'^2} = \overline{\overline{u}^2} + \overline{2\overline{u}u'} + \overline{u'^2} = \overline{u}^2 + \overline{u'^2} = \left(1 + r_u^2\right)\overline{u}^2 \tag{1.16}$$

This means that in reality the Izbash relation should read:

$$\Delta d = B(1 + r_u^2)\frac{u_i^2}{2g} \tag{1.17}$$

In normal cases $r = 0.1$, so in normal wall turbulence $A \approx B$. Although not really known, one may assume that Izbash has derived his equation for a situation with somewhat turbulence. So in his case $B(1+r_u^2) = 0.7 \Rightarrow B = 0.6$. This leads to an adapted Izbash formula of the form:

$$\Delta d = 0.6(1 + r_u^2)\frac{u_i^2}{2g} \tag{1.18}$$

In case of a propeller jet the flow is very turbulent. Experiments in the framework of RIJKSWATERSTAAT/DHL [1988] led to:

$$\Delta d_{50} = 2.5\frac{u_b^2}{2g}\frac{1}{\sqrt{1 - \dfrac{\sin^2\alpha}{\sin^2\phi}}} \tag{1.19}$$

If one disregards the slope correction factor in equation (1.19) and compares the result with equation (1.18), one comes to the conclusion that:

$$0.6(1 + r_u^2) = 2.5 \quad \rightarrow \quad r_u = 1.75 \tag{1.20}$$

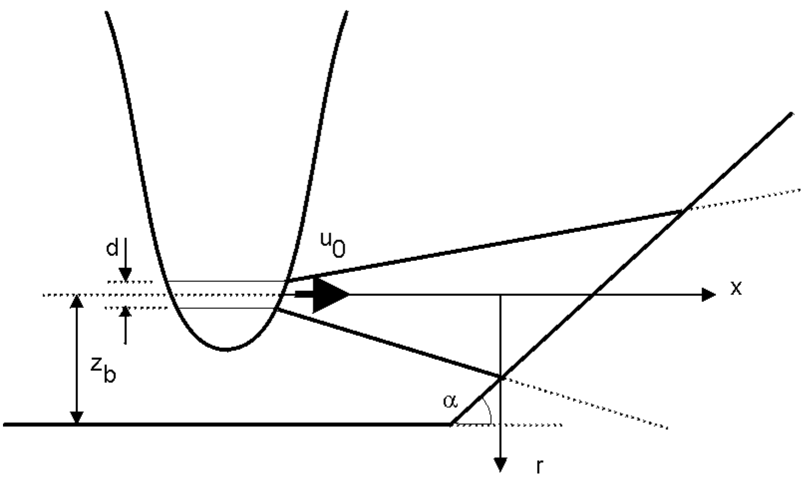

Figure 6: flow from a propeller

From the above follows that measuring the turbulence intensity of the flow in the propeller jet is very important, and perhaps even more important than the average velocity itself. Especially in those conditions where the average velocity is relatively low, but there is a high degree of turbulence, rather heavy stones may be required. For example when the propeller flow hits the slope, part of the flow will be directed upward, and part will be directed downward. At the point where this change takes place (that is approximately where the centre line of the propeller flow meets the slope) the average velocity will be zero, but the turbulence is quite high. At exactly that point one may expect considerable damage.

Conclusions

From the analysis follows that stability of riprap on a slope attacked by propeller flow can be calculated using an Izbash-type of equation, however on should include in this equation explicitly the effect of turbulence. This can be done. Comparing the resulting equation with experimental prototype data of damage leads to the conclusion that under prototype conditions the flow has a relative turbulence in the order of $r = 1.75$. This is a very high value. Therefore further research in the lab is needed to measure the degree of turbulence in the propeller flow of both the main screw as well as in the bowthruster flow.

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