The Influence of Pressure Fluctuations on the Flow Between Armour Elements

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Abstract

To reduce the high expenses of armour layers for the protection of sandy beds in rivers and coastal areas around structures a so called geometrically open armouring, consisting of a single layer of large rocks, is often tried nowadays. In most models it is assumed that the mean flow (and shear stress) above the armour layer penetrates in the pores between the armour elements and that this penetrated flow is responsible for the erosion of the sand bed below the armour layer. However, the relatively thin armour layer these models predict does not always suffice for a safe armouring of the sand bed in practice. Measurements of the flow velocities in the pores between armour elements in a flume using the laser-Doppler technique suggest a completely different erosion mechanism. Erosion appears not to be caused by the mean pore flow. Instead small-scale locally generated velocity fluctuations in the pores lift the sand particles from the bed; large-scale fluctuations, due to large-scale turbulence in the main flow, transport the sand particles through the armour layer into the flow above.

Introduction

In coastal areas and rivers, cover layers consisting of rocks or other armour elements are applied locally to protect the underlying sandy bed from erosion. Armour layers are used:

- as bed defense in rivers
- around piers and other structures
- around breakwaters and groynes
- downstream of sluices

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- at the toe of dikes and banks
- as "falling aprons"

The dimensions of the rocks used and the thickness of the cover layer are chosen such that the underlying sand bed is shielded from the eroding currents and waves. A relatively safe armouring, so-called geometrically closed armouring, consists of several layers of rocks of different dimensions, such that the rocks in a layer cannot escape through the holes between the rocks in the next higher layer, see figure 1. To reduce the very high expenses of this way of armouring a single layer of large rocks, so-called geometrically open armouring, is often tried nowadays, however with at best varying success.

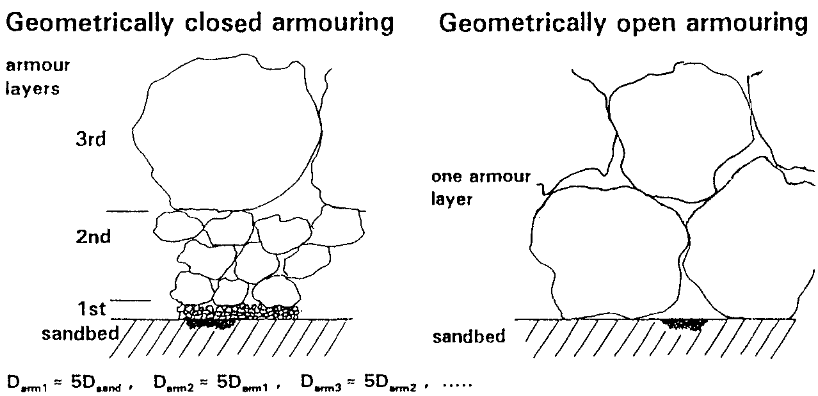

Figure 1. Geometrically closed and open armouring.

In most models that are used for the design of rock beds it is assumed that a direct coupling exists between the mean flow above the bed and the flow through the porous bed. The mean velocity profile is supposed to penetrate a certain distance into the bed and the turbulent fluctuations in the bed to be generated locally by the flow between the rocks. Beyond this distance only a small depth-independent pore velocity, v_p, remains, driven by the same pressure gradient (or slope) as drives the main flow above the armour layer, see figure 2. This pore velocity leads to a very small shear stress at the sand bed below the rocks and a supposedly small erosion. This suggests that in general a relatively thin single rock layer would suffice for a safe armouring.

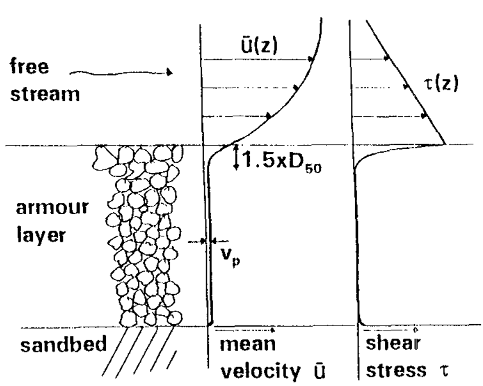

Figure 2. Penetration of main flow.

From a fluid mechanical point of view, however, one can expect that the turbulence present in the main flow above the armour layer generates pressure fluctuations that in their turn lead to a fluctuating flow through the pores of the armour layer. These flow fluctuations may have an important influence on the erosion of the sand bed. Introductory measurements of the fluid velocity and its fluctuations inside the armour layer were executed in order to find out which erosion mechanism is predominant.

Experimental setup

The fluid velocity and its fluctuations inside the armour layer were measured in a flume of the Laboratory of Fluid Mechanics of the Delft University of Technology, using the well-established laser-Doppler (LDA) technique. The typical diameter of the rocks used for the armour layer in the experiments was D_{r50}= 21 mm, and of the sand below this rock bed D_{b50}= 0.10 mm. The ratio of over 200 between the two diameters makes this a case of geometrically open armouring. Optical access to a cavity in the rock bed was established by guiding the laser beams through the bed using small tubes that have negligible effect on the flow (see figure 3). Special care was taken to avoid distortion of the natural rock configuration around the location of measurement. Doing so it was possible to measure the horizontal velocity component between the rocks of the armour layer. The measurements reveal the mechanism of flow generation in the porous bed.

Figure 4 shows an example of a histogram of instantaneous velocities from a time series of 200 seconds, measured 5 cm beneath the bed-stream interface for a 30 cm deep free surface flow. It shows that the mean velocity is small (in this example ≈ 0.6 cm/s), whereas the standard deviation of the velocity fluctuations is rather large (≈ 0.9 cm/s). This velocity distribution suggests that the fluctuating velocities do not stem from the mean flow through the bed. Instead they might be related more directly to the turbulence of the flow over the bed in the following way: The large turbulence scales in the main flow lead to pressure fluctuations at the bed-stream interface. The fluctuating pressure gradients, which can be much larger than the pressure gradient associated with the mean flow, induce a fluctuating flow through the rock bed.

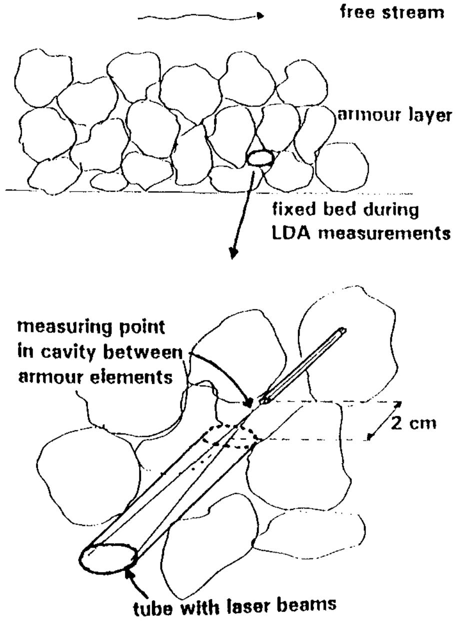

Figure 3. Schematic side view of the laser-Doppler velocimeter set-up.

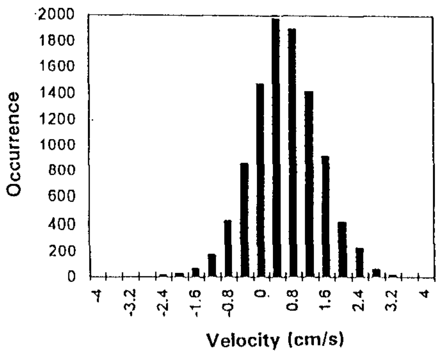

Figure 4. Histogram of pore velocity.

To investigate the consequences for the erosion of the sand bed, part of the flume was covered by a caisson acting as a lid over the water flow, see figure 5. In the resulting slit both the large turbulence scales and the flow velocity could be varied by adjusting the height of the slit S and the water level difference upstream and downstream from the caisson (or the hydraulic gradient in the slit).

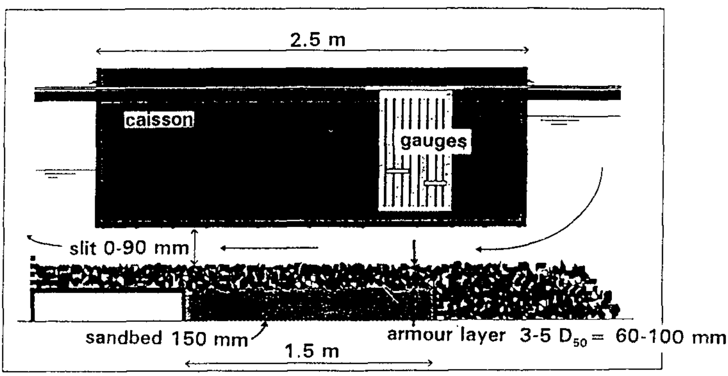

Figure 5. Experimental setup.

The measurements were all executed at a value of the hydraulic gradient just below the critical valuc at which the sand bed starts to erode. This critical value was well-defined as the rate of erosion started abruptly to grow with increasing hydraulic gradient, see figure 6. As LDA measurements require transparent water the sand bed was replaced by a fixed bed during those measurements. The LDA measurements were executed directly above the fixed bottom beneath a 10.5 cm thick armour layer and at the critical hydraulic gradient, i_{cr}, determined in advance in experiments with a sand bed.

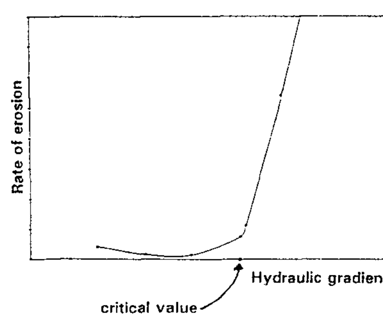

Figure 6. Determination of the critical hydraulic gradient.

Results of the measurements in the armour layer

The LDA measurements yielded mean values and fluctuations of the longitudinal velocity component of the pore flow at the measuring volume in the cavity. Table 1 gives the dependence of the mean pore velocity v_p on the height of the slit. Considering that all measurements were at the critical hydraulic gradient, the results in table 1 show that the mean pore flow is not the cause of the erosion of the sand bed below an armour layer. If that was the case an equal mean pore velocity was to be expected as only the flow condition changes, whereas all other conditions of cavity and bed remain unchanged. Moreover the magnitude of the mean pore flow appears not to be sufficient to lead to erosion. (The critical bed shear velocity of the sand according to the Shields condition is $u_{*cr} \approx 0.6$ cm/s).

S (cm)	i_{cr} (%)	v_p (cm/s)
2.0	4.9	3.91
3.0	4.4	3.61
5.0	3.9	2.50
7.0	3.4	2.15
9.0	3.0	2.28

Table 1. Mean pore velocity.

The cause of the erosion has to be found in flow fluctuations. To investigate this, the autocorrelation functions of the velocity fluctuation were determined. Figure 7 gives an example. Two time-scales are apparent, a large time-scale (of the order of half a second) and a small time-scale of less than 20 ms. (The sample rate used does not allow resolution of the small-scale autocorrelation.) Thus, two kinds of flow fluctuations are present: the small-scale fluctuations, due to locally generated turbulence or small eddies behind flow separations at irregularities in the pore walls, which may be carried away by the mean pore flow, and large-scale fluctuations, caused by the free stream turbulence in the main flow above the armour layer.

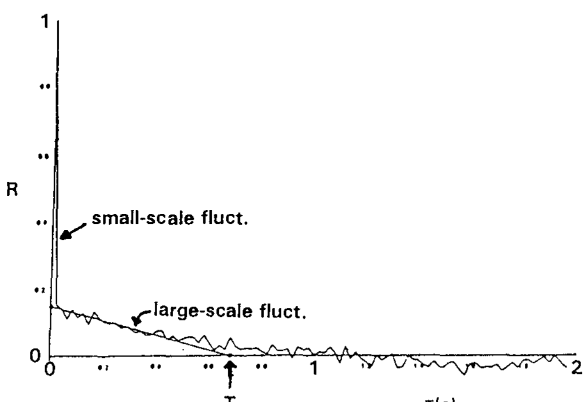

Figure 7. Example of an autocorrelation function, R(τ).

Measured values for both kinds of fluctuations in a series of experiments with different slit heights S are combined in table 2. The columns give respectively S and the measured values for the standard deviation of the small-scale velocity fluctuations σ_h, the standard deviation of the large-scale fluctuations σ_l, the longest time-scale of the fluctuations observable in the correlations T_l and the estimated vertical distance L over which the sand particles move (see below).

S (cm)	σ_h (cm/s)	σ_l (cm/s)	T_l (s)	L (mm)
2.0	1.65	0.65	.18	40
3.0	1.44	0.72	.14	35
5.0	1.30	0.46	.27	39
7.0	1.18	0.40	.26	32
9.0	1.21	0.38	.31	36

Table 2. Measured characteristics of the velocity fluctuations.

From the results in table 2 the following picture of the erosion of the sand bed below a geometrically open armour layer emerges. The very short time scales of the small-scale fluctuations mean that in the flow between the armour elements strong accelerations occur. These accelerations are caused by strong pressure gradients in the flow. The forces on the sand grains by these pressure gradients initiate the lifting of the sand grains from the sand bed. However these pressure gradients last too short to displace the grains through the armour layer. The large-scale fluctuations, which are too slow to generate strong enough pressure gradients to do the initial lifting, move the grains through and out of the armour layer into the free stream.

The estimated distance L over which the sand grains are displaced by the large-scale fluctuations is taken proportional to the standard deviation σ_l and the time-scale measured. For the beginning of erosion the strongest and longest lasting fluctuations are important. Fluctuations of 4 or more times the standard deviation σ_l are present and a few fluctuations lasting about 10 times the time-scale T_l were observed in the executed flow measurements, see figure 8 (which is taken from a different measurement). This is taken into account in the estimated value for L:

$$L = (4 \cdot \sigma_l) \cdot (10 \cdot T_l)$$

Considering the large uncertainty in the measurement of T_l, the valuc for the displacement distance L estimated in this way (see table 2) is a consistent fraction of the total thickness of the armour layer, more or less independent of the slit height. This is what is to be expected as all measurements are executed at the same erosion condition. The time-scale and the standard deviation of the large-scale fluctuations appear to determine thc erosion.

The small-scale fluctuations are generally strong enough to perform the initial lifting.

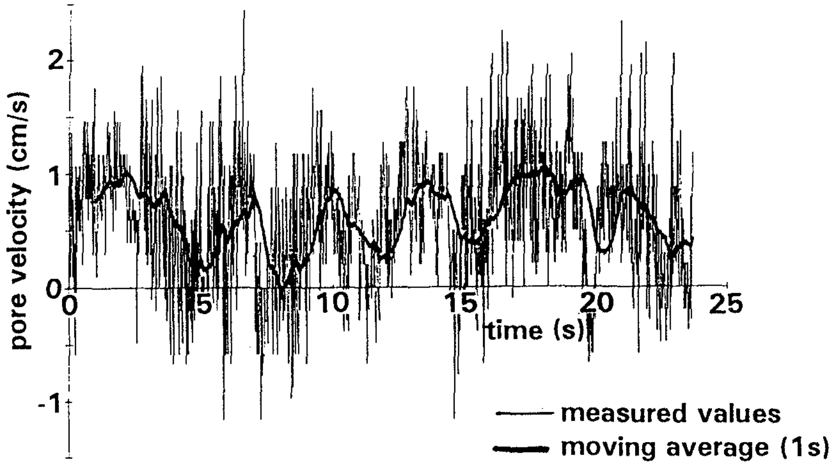

Figure 8. Presence of very large time scales.

Conclusions

In the flow between the armour elements several contributions can be distinguished:

- Mean pore flow. In the upper part of the armour layer it concerns penetrated main flow; deeper in the armour layer the mean pore flow is driven by the hydraulic gradient which also drives the main flow above the armour layer.
- Small-scale fluctuations: locally generated turbulence or small eddies behind flow separations at irregularities in the pore walls, which may be carried away by the mean pore flow.
- Large-scale fluctuations due to turbulence in the main flow.

Based on the magnitudes and characteristics of the different flow contributions between the armour elements the following erosion mechanism is derived:

- Contrary to the assumption used in most models erosion is not caused by the mean pore flow.
- The small-scale fluctuations lift the sand particles from the bed.
- The large-scale fluctuations transport the sand over the armour layer into the flow above.
- The erosion appears to be determined by the time-scale and standard deviation of the large-scale fluctuations. The small-scale fluctuations are generally strong enough to perform the initial lifting.

The conclusions above mean that the design of geometrically opcn armouring requires knowledge of the large-scale turbulence in the main flow and on the large-scale fluctuations it brings about in the armour layer.

Analogous processes can be observed with pressure fluctuations under waves due to the wave motion itself or associated with the turbulence under the waves. Knowledge concerning the erosion processes due to the large turbulent fluctuations above the bed as well as the fluctuations under waves are of key importance for the design of the armouring for the protection of erodible beds.

To give the conclusions reached above a firmer base, further research is suggested:
To check the description of the erosion process:
- measurements of correlations of velocities and pressures in and above the armour layer,
- check on the presence of very large-scale turbulence in the main flow above the armour layer,
- high frequency velocity measurements,
- measurements at more places in one cavity,
- measurements with larger slit height (or free flow depth).

To be able to predict the erosion for armouring design:
- measurements with different armour elements (e.g. size, form or stacking),
- measurements in armour layers below a free surface flow,
- measurements under different turbulence conditions (e.g. in wake flow or the flow behind a sill or pier).