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SHEAR VELOCITY MEASUREMENTS AND SEDIMENT TRANSPORT IN THE SCHELDT ESTUARY

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SUMMARY: An attempt is made to determine the value of U_* (shear velocity) in the estuary of the Scheldt between Hoboken and Ballastplaat. The value of U_* is different for each measuring station and varies between 3.50 cm/sec and 11.30 cm/sec. The consequences from these results in relation to sediment transport are discussed.

1. *Introduction*

Several studies (INMAN 1949 and STERNBERG 1968), concerning the erosion and transport of sediments in rivers, have shown the greater importance of using the shear velocity (U_*) in relation to sediment transport, instead of the average velocity (HJULSTROM 1939) or the velocity at 1 m above the bottom (SUNDBORG 1963).

Yet the accurate determination of U_* seems to be rather problematical. This is the reason why, as a first approach, the value of U_* of a series of vertical velocity distributions, measured at 6 stations localized in the section of the Scheldt estuary between Hoboken and Ballastplaat (fig. 1) has been determined.

An attempt has also been made to draw some conclusions from the values of U_* found in this way (at least as far as they are reliable) about the sediment transport in this section of the estuary.

2. *Methods*

The measurements have been accomplished with an OTT-current meter, which implies a certain time lag to exist between the first and the last measurements on a given vertical and thus no simultaneity in the measurements. There is also an error due to the type of current meter used (error which can be estimated at 5%). There are also errors due to inaccurate determination of the measuring depth below the surface and to vertical and horizontal movements of the ship.

3. *Measurements and calculations*

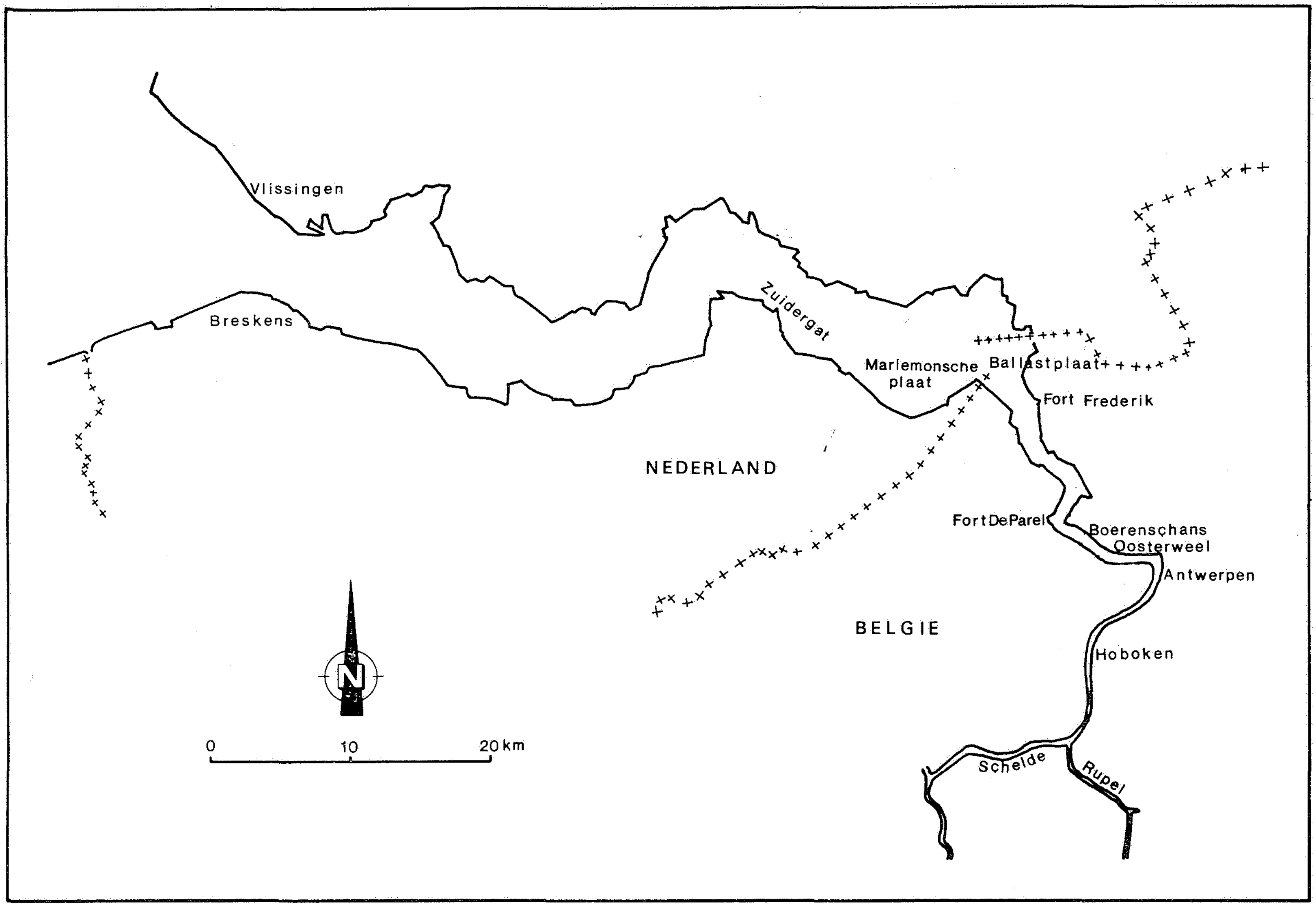
From observations in nature (VAN VEEN 1936, STERNBERG 1968) and from laboratory experiments (KEULEGAN 1938, VANONI 1946 and 1952) it has been found that the vertical velocity distribution in rivers satisfies the "Von Karman - Prandtl" equation:

$$\frac{U}{U_*} = \frac{U_M}{U_*} + \frac{2.3}{k_o} \log_{10} \frac{Z}{H} \qquad (1)$$

(the explanation of the symbols is given at the end of the text).

As can be seen, this equation considers the value of the shear velocity. Several scientists therefore have used it for their studies on sediment transport (SVERDRUP 1942, INMAN 1949, BRIGGS and MIDDLETON 1965, STERNBERG 1968, MC CAVE 1970, KACHEL and STERNBERG 1971).

Nevertheless none of these studies (except these of STERNBERG) describes a method for


Vlissingen
Breskens
Zuidergat
Marlemonsche plaat
Ballastplaat
Fort Frederik
NEDERLAND
FortDeParel
Boerenschans
Oosterweel
Antwerpen
BELGIE
Hoboken
Schelde
Rupel
N
0
10
20 km

measuring the value of U_* under natural circumstances, nor discusses if it is possible to do so.

Thus the question arises if it is possible to calculate a value for U_*, given a known vertical velocity distribution, based on some 10 velocity measurements between bottom and water surface.

BAGNOLD (1941) and STERNBERG (1968) showed that the value of U_* is proportional to the slope of the vertical velocity distribution, as far as a logarithmic z/H ordinate is used. The major problem seems thus to have an accurate and simultaneous measurement of the velocity of the water on each point beneath the water surface.

Inaccuracies, due to the technique used, thus necessitate a statistical approach of the data obtained. Two statistical parameters give an idea of the degree of reliability between the measurements and the "Von Karman-Prandtl" equation. The first parameter, a correlation coefficient (RO), has a value of one when a perfect agreement is obtained, while a smaller value corresponds to a deviation from equation (1). Values between 0.95 and 1.00 represent a good agreement, values between 0.95 and 0.90 an acceptable agreement. Velocity distributions with values for RO smaller than 0.90 are not considered here.

The variance around U_* that may be expected, U_*INT, is the other statistical parameter. There exists, as will be shown, a positive correlation between the value of U_* and U_*INT. Higher values of U_* give higher values for U_*INT also.

A review of the results, obtained for the different locations, is given in the table. The data mentioned are the number (N) of vertical velocity distributions measured during a 13 hours-cycle, the minimum and maximum values of U_* for each location, the number of verticals having a value of RO between 0.90 and 0.95, and the number of verticals having a value of RO superior to 0.95.

As can be seen in the table, 23% of the measurements give an acceptable value for U_* and 43% even a good value. These percentages are somewhat low because for 6 verticals a good agreement with the "Von Karman-Prandtl" equation is found in the lowest part of the measured vertical. The velocities in the 30% uppermost layers however showed high deviations causing aberrant values for U_* and thus very low values for RO. It can be admitted that, if the value for U_* should be calculated for the underlying layers separately, a better agreement will be found. In this case 79% of the measured verticals give at least an acceptable result for U_*.

TABLE

Location	N	$U_{*\,min}$	$U_{*\,max}$	RO (0.90)	RO (0.95)
Hoboken	8	3.50	6.30	5	1
Oosterweel	7	4.00	8.20	1	5
Boerenschans	10	1.30	7.50	4	1
Fort De Parel	10	5.20	8.10	1	9
Fort Frederik	13	1.70	7.30	1	5
Ballastplaat	13	2.70	11.30	2	7
Total	61			14	28
%	100			23	43

RO (0.90): number of measurements giving a value of RO between 0.90 and 0.95
RO (0.95): idem for RO superior to 0.95
U_* values expressed in cm/sec

As has already been stated, there seems to exist a positive correlation between U_* and U_*INT (fig. 2). Higher values of U_* correspond to higher values of U_*INT. Further two cases can be considered. In the first case, considering all the measures giving a value of $RO > 0.90$, the correlation can be expressed by the equation:

$$U_*INT = 0{,}21\, U_* - 0{,}07 \qquad (2)$$

indicating that U_* is determined with an error of some 20%.

When values of $RO > 0.95$ are considered, a correlation, expressed by equation (3) is found:

$$U_*INT = 0{,}073\, U_* + 0{,}65 \qquad (3)$$

In this second case the deviation is only 7% and the results are considered as good.

The values of U_* obtained in this way scatter between 1.30 and 5.20 cm/sec for the minimum values (see table) and between 6.30 and 11.30 cm/sec for the maximum values.

Although there is no indication for a progressive evolution of the value of U_* between Hoboken and Ballastplaat, it is to mention that the lowest maximum values of U_* were measured at Hoboken and the highest ones at Ballastplaat.

It is expected that new experiments with a better equipment (measurements made only in the bottom layers) will give more accurate indications about the value of U_* in the estuary of the Scheldt.

4. *Effects on sediment transport*

The suspension concentration on a vertical in the river can be expressed by the following equation (Inman 1949):

$$\log_{10}\frac{C_z}{C_a} = -\frac{1}{k_o}\,\frac{\omega}{U_*}\,\log_{10}\frac{z}{a} \qquad (4)$$

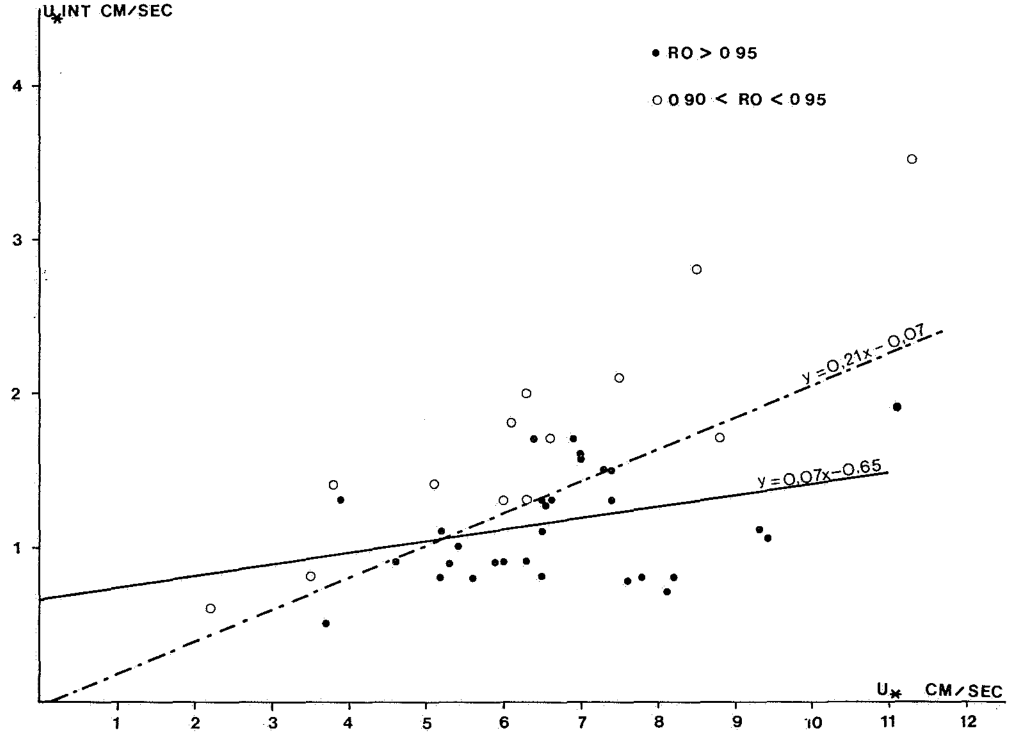


Fig. 2.

If fixed values for z and a are selected so that:

$$\frac{z}{a} = 10 \tag{5}$$

then equation (4) shows that any curve for which the ratio U_*/ω equals a constant:

$$\frac{U_*}{\omega} = n \tag{6}$$

is a curve along which the concentration ratio C_z/C_a is also a constant (INMAN 1949):

$$\log_{10} \frac{C_z}{C_a} = -n \frac{1}{k_o} \tag{7}$$

From $k_o = 0.4$ and $n = 1$ follows that:

$$\log_{10} \frac{C_z}{C_a} = -2.50 \tag{8}$$

INMAN (1949) and before him LANE and KALINSKE (1939) and KALINSKE (1941) suggested that a value of $n = 1$ for the ratio of the shear velocity to the settling velocity is a criterion for the beginning of suspension. This is in agreement with Von Karman's statement (VON KARMAN 1935) that, for an isotropic turbulence, the shear velocity equals the mean of the absolute value of the velocity fluctuations.

In fig. 3 the suspension concentration for a series of values of n is calculated. At the same time these curves give an idea of the suspension composition at various depths and for a given value of U_*, assuming that the suspension composition near the bottom equals this of the bottom sediments.

At most locations the maximum value of U_* is about 8 cm/sec. In this case sediment particles with a diameter of 0.500 mm to 0.600 mm correspond to a value $n = 1$. These particles are thus to expect to be the largest of being transported in suspension, at least close to the bottom. For the same value of U_* a value of $n = 2$ corresponds to particles with a diameter of 0.250 mm, particles which will be transported in suspension up to 10% of the waterdepth (fig. 3). All sediments having a smaller diameter will be found in suspension up to the water surface.

Fig. 3. Concentration variation with depth of sediment particles with given fall velocity (ω) for different values of U_*. The concentration of the considered particles on the bottom is taken as 100%.

If the value of U_* is as low as 3 cm/sec, then sediment particles of 0.250 mm can be hardly brought into suspension, all coarser sediments are now carried as bottom transport or not at all.

Considering now these results in the light of the grain size analyses of bottom sediments from the mean channel and the tidal flats of the Scheldt, it is easy to observe that from Hoboken (samples M4 and M8, fig. 4) to Antwerp (M11 and M13) sediment particles coarser than 0.500 mm gradually disappear. At the other side of the considered section, near Ballastplaat, the bottom sediments are coarser again (sample B24, fig. 5).

This is in good agreement with the values of U* found in these parts of the river which indicate particles coarser than 0.500 mm to be hardly transported at Hoboken but easy at Ballastplaat.

On the tidal flats sediments coarser than 0.250 mm are lacking (fig. 6, representing sediments from the tidal flats in front of Antwerp and fig. 7, sediments from the tidal flats near Ballastplaat). This also is in good agreement with the values of U* found, which indicate that the coarsest particles to

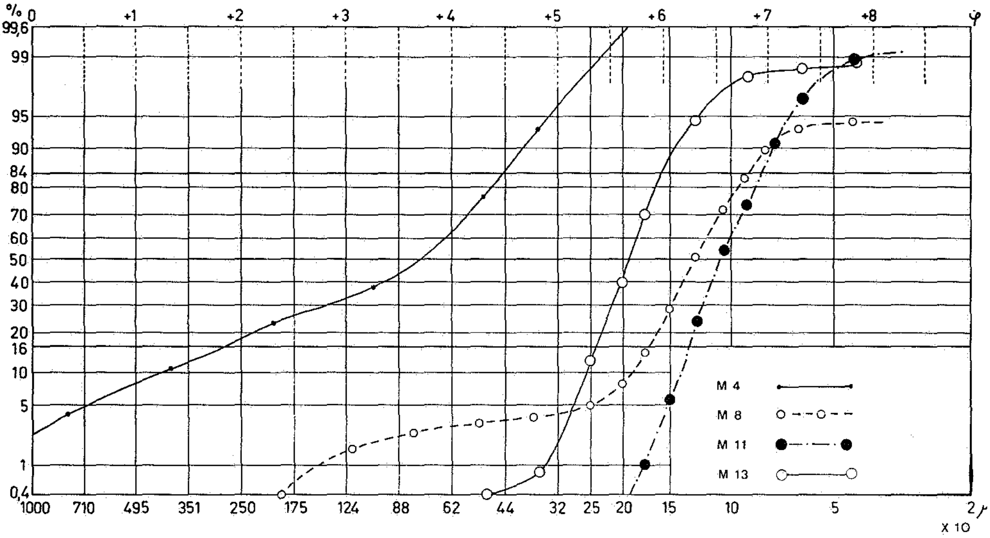


Fig. 4. Grain size analyses of bottom sediments between Rupelmouth and Antwerpen.

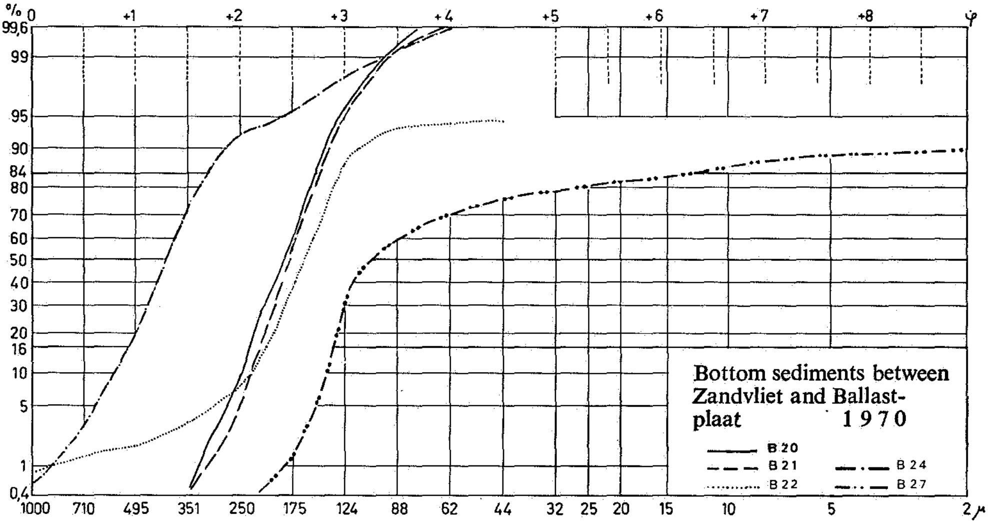
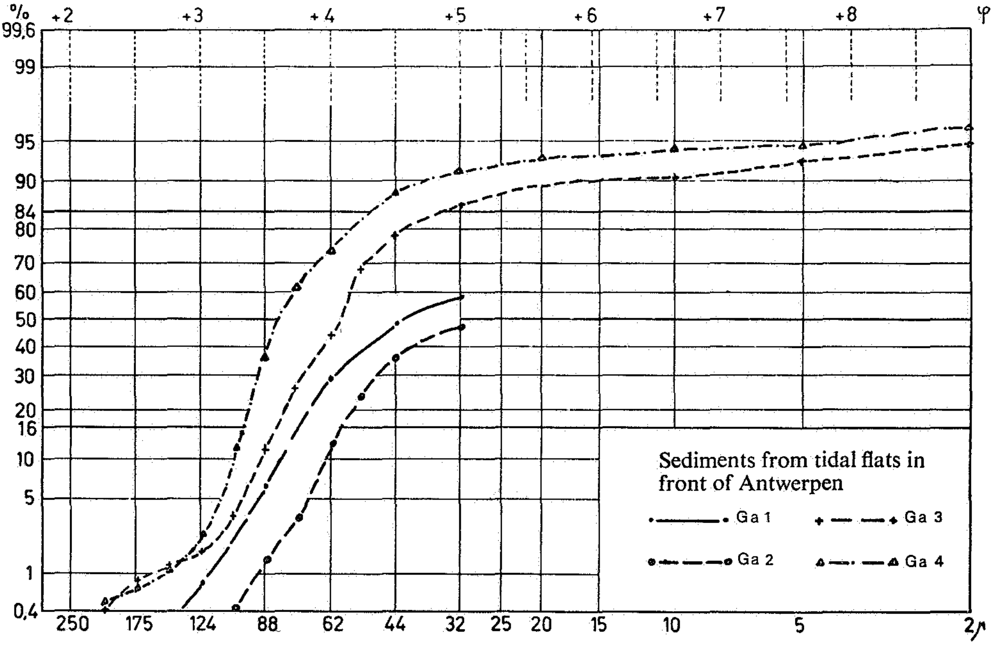


Fig. 5.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Sediments from tidal flats in front of Antwerpen
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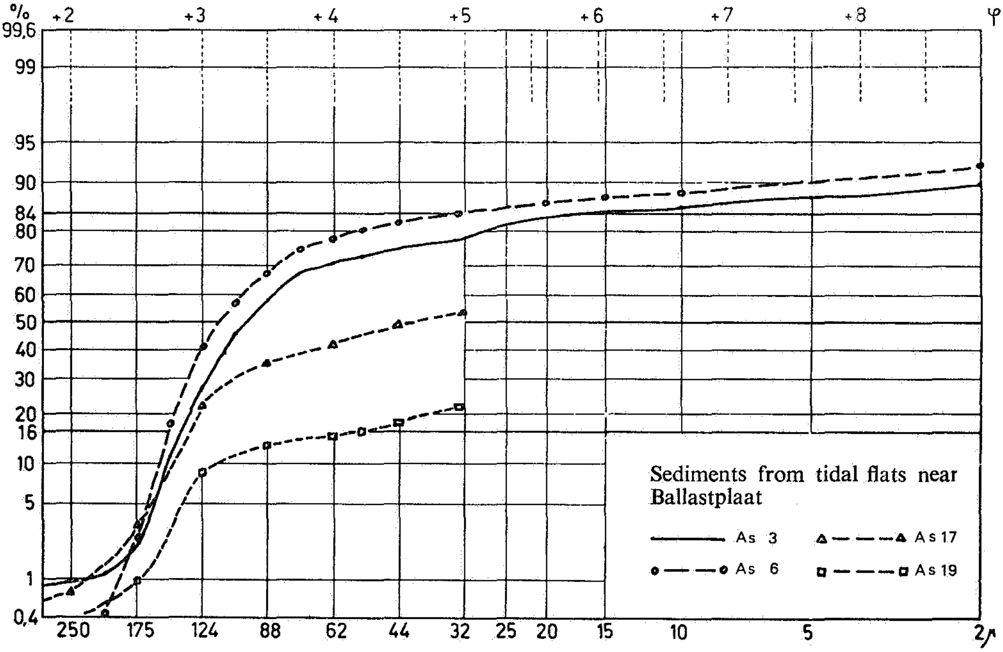
Fig. 6.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Sediments from tidal flats near Ballastplaat
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Fig. 7A.

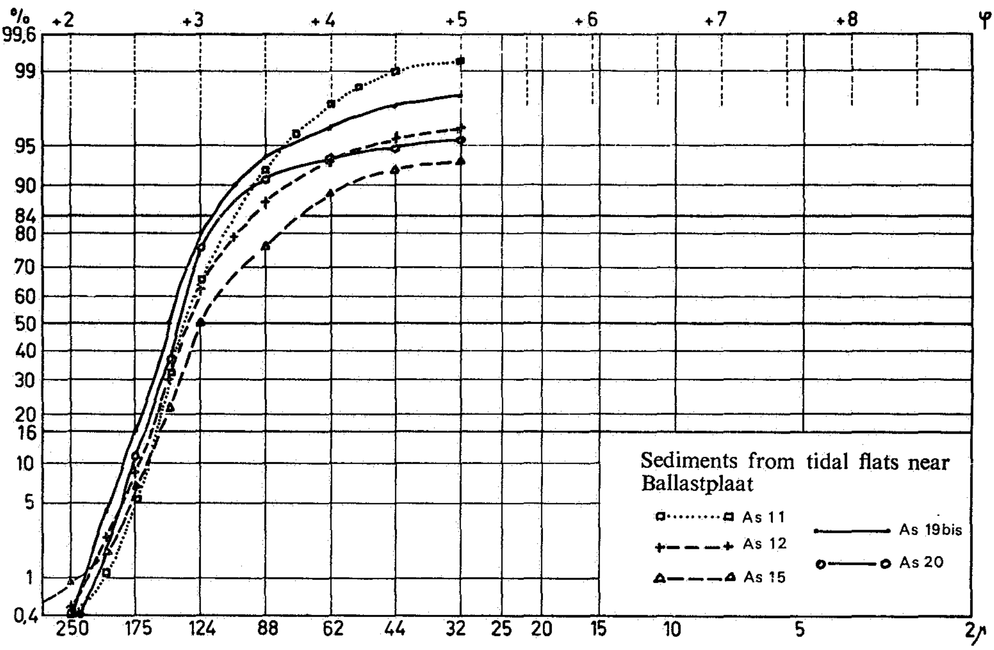

Fig. 7B.

be expected in suspension at a certain distance from the bottom are never superior to 0.250 mm.

The problem becomes more difficult when muddy sediments are concerned. Migniot (1968) states that mud with concentrations of 500 to 700 g/l (measurements made on muds filling up gullies in the tidal flats indicated at their surface concentrations of 600 g/l) can be eroded at shear velocities of 8 cm/sec. Very soft muds from the mean channel have concentrations of 88 to 300 g/l (Peters 1968).

Where the mud deposits from the mean channel will be easely eroded, one can not say the same for the muds on the tidal flats, which need velocities probable higher than these normally occuring in this environment (this is also supported by experiments with fluorescent tracers on the tidal flats, Wartel 1972).

5. *Conclusions*

Calculations, based on the vertical velocity distribution in the estuary of the Scheldt, give for 43% of the measured verticals a satisfactory value for the shear velocity. The value of $U_{*}INT$ does not exceed 10% of the value of U_{*}. 28% of the measurements give an approximating value of U_{*} for which $U_{*}INT$ reaches 20% of the value of U_{*}. The shear velocities, measured in this way, range from 1.7 cm/sec to 11.3 cm/sec. The highest values were found at the Ballastplaat, the lowest maximum values (6.30 cm/sec) at Hoboken.

Application of these data to the possible suspension transport gives an apparent good agreement with the grain size of the bottom sediments from different parts of the estuary.

Using the calculated values of U_{*} a maximum grain size of 0.500 mm is found for the coarsest sediment which can be transported in suspension. Coarser sediments will be transported by rolling or jumping. Also the maximum value of 0.250 mm for the diameter of sediments from the tidal flats finds an explanation by the data obtained for U_{*}. Mud deposits on the other hand seem to be easely eroded and transported in suspension as far as their concentration does not exceed 500 to 700 g/l. These concentrations were found for muds in the channels of the tidal flats.

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LIST OF SYMBOLS USED

symbol	*explanation*	*dimensions*
a	reference depth below the watersurface	cm
C_a	suspension concentration at a depth a	g/l
C_z	idem at a depth z	g/l
H	total waterdepth at the measuring moment	cm
k_o	Von Karman constant	none
RO	correlation coefficient	none
U	velocity of the water	cm/sec
U_M	maximum velocity of the water at a given vertical	cm/sec
U_*	shear velocity	cm/sec
U_*INT	variance of U_* to be expected	cm/sec
z	measuring depth	cm

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