The use of artificial roughness in movable-bed models

Summary.
Tests have been done in a laboratory flume, to evaluate the influence of vertical rods of 3 mm dia on the hydraulic and sedimentological characteristics of the flow.

The first report deals with the measurements with fine bakelite and waterdepths 10 and 5 centimeters.

The second report deals with the measurements with fine sand and the same waterdepths.

The results must be carefully interpreted as follows from the two conclusions.

Note
The tests have been carried out and evaluated by participants of the International Course in Hydraulic Engineering as a practical groupwork in this course.
Summary.

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Summary

Tests have been done in a laboratory flume, to evaluate the influence of vertical rods of 3 mm dia. on the hydraulic and sedimentological characteristics of the flow.

The first two tests have been done with some 10 cm waterdepth. In both tests the same flow rate and sediment transport was used, the only difference between the tests being the artificial roughness, which was applied during the second test.

The following two tests were done in a similar way with a waterdepth of about 5 cm and with a reduced flow rate and sediment transport. For both 10 cm and 5 cm waterdepths, the bar resistance was then measured in the flume without bakelite.

The influence of the rods on the ripple factor, $\mu$, thus on the bottom roughness, could be evaluated, after elimination of the bar resistance.

In the case of 10 cm depth, the artificial roughness caused a reduction of bottom roughness, while with a depth of 5 cm an increased bottom roughness with the bars was found.

By calculating the bed load from the product of the mean ripple celerity and half the mean ripple height a very good agreement was found with the actually measured quantities.
Report no. 1
Tests with bakelite

The use of artificial roughness in movable-bed models

1. Introduction.

Incompatible scale relationships for the several channels of a proposed hydraulic model, to be built with a movable bed, led to the conclusion that the roughness of one of the principal sections should be artificially increased. To the knowledge of the authors artificial roughness has never previously been applied to movable bed models. Thus, it was decided to conduct flume tests in an attempt to discover in what way the imposed roughness would influence the bed load movement; and in this way formulate recommendations for the application of this technique to hydraulic model studies.

The tests were conducted from March to June 1962 at the Hydraulics Laboratory, Delft. Testing was restricted to the only flume available in the laboratory which had dimensions:

- Length: 30 m.
- Width: 0.30 m.
- Depth: 0.35 m.

Two materials, fine bakelite and sand, were tested. For each material two phases of transport (according to the transport formula of Frijlink) were considered. The tests on each material were made by different groups, and the following report deals solely with those tests using fine bakelite. The second part of the report contains the results obtained using sand.

The tests have been done under the guidance and with the assistance of Messrs. J.E. Prins and H.N.C. Breusers of the Hydraulics Laboratory, by:

- J.A.T. Aspden
- I.J. Wainer
- D.R. Wells
- J.A. Zwamborn,

2. Description of Tests.

The tests were performed in a 27.5 meter long, 30 cm wide outdoor flume at the Delft facility of the Delft Hydraulics Laboratory. The pertinent dimension and configuration are shown in Fig. no. 1.

A constant discharge was maintained in the 30 x 35 cm$^2$ channel by use of a 70° triangular weir (3). The discharged water was recirculated via a circular reservoir. Assurance of a constant discharge was obtained by observations of the water level (2) in the stilling basin (11) from which water flowed to the triangular weir.

The dynamics of the water were measured in the middle of the flume as shown in the diagram. The slope of the energy line was observed by two pitot tubes situated 10 meters apart (4)-(5) and the waterdepth and surface were observed by two point gauges (6)-(7) 9 meters apart and centered around the same point as the pitot tubes.

A number of stream velocity measurements were made by means of the propellor velocity meter situated between the pitot tube gauges (9). Measurements were taken at enough points vertically to obtain a velocity profile in all cases except those for which the waterdepth only allowed a few measurements. Bakelite was used as a substitute for natural sand.

It was necessary to enable the bakelite transport to come to equilibrium over a period of some hours before tests could be performed. An automatic timer (1) regulated the input of bakelite into the head of the flume. The bakelite was packed in measured quantities into cells over the upstream end of the flume and the timer fed enough water into these cells, one at a time, periodically to wash the bakelite into the flume. The transported bakelite could again be collected and measured in a trap (10) at the downstream end of the flume during a test.

Photos were taken of the ripples at one particular place, at five minutes intervals.

A few samples of the sediment were analysed by sieving in order to attain size distributions.

* No's between brackets refer to Fig. 1.
3. Test results

The average values are summarized in the table below.

Tests with movable bed.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Deep water (h≈10 cm, Q≈8 l/sec)</th>
<th>Shallow water (h≈5 cm, Q≈3 l/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No rods</td>
<td>With rods</td>
</tr>
<tr>
<td>Q (flow in 10^{-3} m^3/s)</td>
<td>8.40</td>
<td>3.10</td>
</tr>
<tr>
<td>h (water depth in 10^{-2} m)</td>
<td>12.1</td>
<td>6.2</td>
</tr>
<tr>
<td>I_e (energy slope)</td>
<td>0.76x10^{-3}</td>
<td>0.99x10^{-3}</td>
</tr>
<tr>
<td>T_t (total bedload in N/hr.)</td>
<td>66.6</td>
<td>16.2</td>
</tr>
<tr>
<td>V = Q/abh</td>
<td>24.4</td>
<td>17.2</td>
</tr>
</tbody>
</table>

\[ V = \sqrt{\frac{Q}{abh}} \]

\[ 10^{-2} \text{ m/s} \]

\[ 23.2 \quad 23.7 \quad 16.7 \quad 14.0 \]

Bakelite

\[ d_m = 0.54 \times 10^{-3} \text{ m} \]

\[ d_{90} = 0.75 \times 10^{-3} \text{ m} \]

\[ \Delta_s = 1400 \text{ kg/m}^3 \]

Roughness tests.

(without movable bed).

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Deep water 10 cm</th>
<th>Shallow water 5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No rods</td>
<td>With rods</td>
</tr>
<tr>
<td>Q in 10^{-3} m^3/s</td>
<td>8.36</td>
<td>3.10</td>
</tr>
<tr>
<td>h in 10^{-2} m</td>
<td>11.15</td>
<td>6.22</td>
</tr>
<tr>
<td>I_e</td>
<td>0.33x10^{-3}</td>
<td>0.19x10^{-3}</td>
</tr>
<tr>
<td>V in 10^{-2} m/s</td>
<td>25.2</td>
<td>16.5</td>
</tr>
<tr>
<td>V = \sqrt{\frac{Q}{abh}}</td>
<td>25.0</td>
<td>16.5</td>
</tr>
<tr>
<td>10^{-2} \text{ m/s}</td>
<td>25.0</td>
<td>16.5</td>
</tr>
</tbody>
</table>
The following additional remarks can be made.

Flow measurement was done with the $70^\circ$ sharp edged V-notch for which the calibration is shown in fig. 2. Both the relationship $Q = 1.4xH^{2.5} \tan \frac{\varphi}{2}$ (Delft) and $Q = 1.34 H^{2.48} \tan \frac{\varphi}{2}$ (King's Handbook of Hydraulics) show an appreciable deviation for $Q < 1.5 \text{ l/s}$ and $Q > 7.5 \text{ l/s}$. A much better fit of the points is obtained with a relation of the type $Q = \text{constant} x H^{2.2}$. Because the measured points, however, do not extend far enough to warrant the acceptance of the power $2.2$ the simpler formula $Q = 1.4 H^{2.5} \tan \frac{\varphi}{2}$ has been used.

This seemed acceptable, because all tests were done with flow rates of $3 \text{ l/s}$ or $8 \text{ l/s}$.

For flow rates of $10 \text{ l/s}$ and over, the possible error, however, may be large.

Velocity measurements were done with a propellor current meter. For the calibration, see fig. 4.

Size distribution curves of the bed material and the bakelite taken from the sediment trap at the low and of the flume are shown in fig. 5. The two materials seem to be virtually the same, although the transported material has a somewhat smaller standard deviation. No general conclusions, however, can be drawn because only one set of curves was obtained. The total transport for each test was known from the feeding rate, which in itself was verified by measuring the sediment caught at the end of the flume.

Ripple dimensions and celerities have been recorded photographically and the results have been summarised in fig.'s 6, 7 and 8 for the 10 cm depth.

4. Basic calculations

4.1. The transport theory according to Frijlink can be plotted, as shown in figure 1, using the parameters:

$$\frac{T_b}{d_m^{3/2} \sqrt{\Delta \gamma}}$$ and

$$\frac{\Delta \cdot d_m}{\mu h t}$$

$T_b$ = volume of bottom transport/unit width.

$d_m$ = mean grain diameter.

$\Delta = \frac{\rho_b - \rho_w}{\rho_w}$

$\rho_b$ = density of bottom material

$\rho_w$ = density of water.
\[ \mu = \text{ripple factor, according to Frijlink: } \mu = \left( \frac{C}{C_{\text{grain}}} \right)^{3/2}. \]
\[ h = \text{depth of water.} \]
\[ I = \text{slope of energy line.} \]
\[ C = \text{Chezy roughness coeff.} \]
\[ C_{gr} = C_{d90} \text{ (grain roughness).} \]

Approximately the two following phases of transport were considered:

\[ (1) \quad \frac{T_b}{d_m^{3/2} \sqrt{\Delta g}} = 0.2 \quad \quad (2) \quad \frac{T_b}{d_m^{3/2} \sqrt{\Delta g}} = 0.04 \]

The depth of water taken for each phase of transport was 0.1 m and 0.05 m respectively.

From the sieve analysis, figure 4,
\[ d_m = 0.54 \times 10^{-3} \text{ m.} \]
\[ d_{90} = 0.75 \times 10^{-3} \text{ m.} \]
Also \( \rho_s = 1400 \text{ kg/m}^3 \), giving \( \Delta = 0.4 \).

The computed values are:

(1) \( h = 10 \text{ cm} \)
\[ \mu = 0.44 \quad \quad \mu = 0.52 \]
\[ I = 0.61 \times 10^{-3} \text{ m} \]
\[ \bar{v} = 0.24 \text{ m/sec} \]
\[ Q = 7.8 \times 10^{-3} \text{ m}^3/\text{sec} \]
assumed ripple roughness:
\[ k = 1/3 \text{ ripple height} = 2 \text{ cm} \]

These values may be compared with the results of the measurements.

4.2. Side wall influence

In consideration of the limited width of the channel it was necessary to take the roughness of the side-walls into account when calculating the bottom roughness from the experimental results. This was done in the following manner.

The formula of flow according to de Chezy:

\[ V = C \sqrt{IR}, \]
V = velocity, \( R \) = hydraulic radius, \( I \) = slope of energy line,
\( C \) = a coefficient of roughness, based on the logarithmic velocity distribution
\( = 18 \log \left( \frac{12R}{k + \delta/4} \right) \),
\( K \) = a roughness factor for the material considered or the bed form,
\( \delta \) = the thickness of the laminar sublayer (in case of movable bed negligible).

(1) Assume first that the walls of the channel are perfectly smooth, i.e. there is no wall friction.

Then

\[ R_b = \frac{hxB}{b} = h. \]

thus

\[ I_b = \frac{v^2}{C_b h} \]

(II) Maintaining the same velocity, assume now that the bottom is completely frictionless.

Then

\[ R_w = \frac{hxB}{2h} = \frac{B}{2}. \]

thus

\[ I_w = \frac{2v^2}{C_w B} \]

Also: \( C_w = 18 \log \left( \frac{6B}{k_w + \delta/4} \right) \).

Thus \( I_w \) is seen to be independent of the depth of water \( h \), and to tend to zero as \( B \) increases. Combining:

\[ I_{total} = I_b + I_w \]

\[ = \frac{v^2}{C_b h} \left[ \frac{1}{C_b h} + \frac{2}{C_w B} \right] \]

or

\[ v^2 = \frac{C_b^2 C_w^2 B}{C_w B + 2C_b^2 h} h I_{total} \]
Putting \( C_t^2 = \left[ \frac{C_b^2 C_w^2 B}{C_w^2 B + 2C_b^2 h} \right] \) follows: \( V^2 = C_t^2 h I_{\text{total}} \).

When \( I_{\text{total}} \) is known, we have

\[
C_b^2 = \left[ \frac{C_t^2 C_w^2 B}{C_w^2 B - 2C_t^2 h} \right].
\]

The wall roughness \( C_w \) can be found by assuming a value of \( k \) for the wall material.

4.3. Bar resistance

It was proposed that the artificial roughness should take the form of wire spokes suspended from a framework over the channel, and extending into the bottom material.

Two reports (Ref. 1 + 2) were found to exist which investigate the effect of such vertical roughness elements on the flow of water in fixed bed channels. The latter of these reports was used to estimate the necessary density of the roughness elements, and the results obtained were compared with the graphs given in the former report. The agreement was satisfactory.

Method:

Consider a reach, length \( L \), of a channel having depth \( h \) and breadth \( B \). The resistance to flow in this channel will be:

\[
\rho gh L I_{\text{e}} = \rho gh BL \frac{V^2}{C^2 R} \quad (1)
\]

Now imagine a bar, width \( b \), to be immersed in the stream over a depth \( h \). The resistance offered to the flow by this bar will be:

\[
\frac{1}{2} C_D bh \rho V^2 \quad \text{and if there are 'n' such bars introduced, the total resistance offered by the bars is:}
\]

\[
\frac{n}{2} C_D bh \rho V^2.
\]
Thus, the total resistance to flow will now be:

$$\rho g FLV^2 \left[ \frac{1}{C^2} + \frac{n \cdot \frac{1}{2} C_D bh}{\frac{FR}{g FL}} \right]$$

where $F = h_x B$.

Alternatively, by assuming a new roughness coefficient $C'$ for the channel with bars, the total resistance can be written:

$$\rho g FL \frac{V^2}{C'^2 R}$$

Thus,

$$\rho g FL \frac{V^2}{C'^2 R} = \rho g FLV^2 \left[ \frac{1}{C^2} + \frac{n \cdot \frac{1}{2} C_D bh}{\frac{FR}{g FL}} \right]$$

or

$$n = \frac{2g FL}{C_D bh} \left[ \frac{1}{C'^2 R} - \frac{1}{C^2 R} \right]$$

Further, the number of bars per unit surface area

$$n' = \frac{2g}{C_D b R} \left[ \frac{1}{C'^2} - \frac{1}{C^2} \right]$$

4.4. Bar spacing for a particular case.

The value of $C$ for the stages of transport and material used is in the region of $30 \ m^3/s$. For the proposed model which brought about the inception of these tests, it was required to reduce this value to $18 \ m^3/s$.

i.e. $C = 30 \ m^3/s \quad C' = 18 \ m^3/s$.

The spokes used as roughness elements had a diameter of $3 \ mm = d$), and the value of $C_D$, from graphs (Ref 3) for cylindrical bodies is 1.2 with $h = 0.1 \ m$ and $B = 0.30 \ m$;

$$n' = \frac{2 \times 9.81 \times 10^{-3} \times 0.1}{1.2x3x10^{-3} \times 0.1} \left[ \frac{1}{(18)^2} - \frac{1}{(30)^2} \right] = 109/\ m^2 \ .$$

For practical reasons a density of 66.7 bars per square meter was adopted; the spacing being as shown.

[Diagram showing bar spacing]
4.5. The slope ($I_R$) by only the bars.

The resistance to flow caused by the bars can be written either

(I) As the force offered by the bars to the water:

\[ \frac{A}{2} C_D b h \rho V^2, \]

or

(II) In terms of the slope, $I_R$, produced by the bars (small slopes being additive):

\[ \rho g F L I_R. \]

Thus:

\[ I_R = \frac{n C_D b h \rho V^2}{2 \rho g F L} \quad \text{with} \quad F = h \times b \]

or

\[ I_R = \frac{n C_D b V^2}{L B. g}, \]

It is to be noted that the slope is independent of the water depth.

5. Calculations of the results

5.1. Determination of bar resistance for two waterdepths. Test no. V.

No movable bed.

(1) Deep water case

No bars:

| $Q$ | $8.36 \times 10^{-3}$ m$^3$/s |
| $h$ | $11.15 \times 10^{-2}$ m |
| $I_e$ | $0.33 \times 10^{-3}$ |
| $V$ | $Q/h = 0.25$ m/s |
| $R$ | $0.064$ m |

With bars ($b = 3$ mm):

| $Q$ | $8.36 \times 10^{-3}$ m$^3$/s |
| $h'$ | $11.72 \times 10^{-2}$ m |
| $I_e'$ | $0.99 \times 10^{-3}$ |
| $V'$ | $0.238$ m/s |
| $R'$ | $0.066$ m |

To obtain the $I_{\text{total}}$ which is the combined influence of bottom and walls, for the case with bars, the measured slope $I_e$ must be reduced in the following way:

\[ I_{\text{total}} = \frac{V'^2}{V^2/R} \times I_e. \]
It is assumed that with the small change in $R$, the $C$ value is constant.

One finds:

$$I_{\text{total}} = 0.88 \ I_e = 0.29 \times 10^{-3}, \text{ thus } I_R = I'_e - I_{\text{total}} = 0.7 \times 10^{-3},$$

which is the slope due to the bar resistance only.

The value of $C_D$ can now be found from:

$$I_R = \frac{n' C_D bv^2}{2g} \quad C_D = 1.21.$$ 

The assumed value of $C_D = 1.2$ is thus correct.

(2) Shallow water case. $h = 6.2$ and $6.5 \times 10^{-2}$ m.

In the same way as for (1), the following values are found:

$$I_{\text{total}} = 0.90 \ I_e = 0.17 \times 10^{-3} \quad (I'_e = 0.55 \times 10^{-3})$$

$$I_R = 0.38 \times 10^{-3} \quad \text{ and } \quad C_D = 1.47.$$ 

The graph from Rouse gives a value $C_D = 1.3$ for $Re = 480$.

The above values for $C_D$ are very close to the values given by Rouse for a cylindrical body.

5.2. Wall friction. Test no. V.

From the two tests without bars, the $C$ value of the channel can be calculated and from this Chézy roughness value, the $k$ value can be found.

(1) Deep water case.

$$C = 54.3 \ m^2/s, \text{ giving } k = 5 \times 10^{-4} \ m.$$ 

(2) Shallow water case.

$$C = 57.3 \ m^2/s, \text{ giving } k = 0.6 \times 10^{-4} \ m.$$ 

In the latter case, the laminar sublayer becomes important, therefore the first value of $k$ is more reliable.

5.3. Test no. I. Deep water, no bars.

$$Q = 8.40 \times 10^{-3} \ m^3/s, \quad T_b = 66.6 \ N/hr.$$ 

$$h = 0.121 \ m, \quad T_b = 4.5 \times 10^{-6} \ m^2/s$$ 

$$V = \frac{Q}{B \ h} = 0.232 \ m/s$$

$$I_E = I_{\text{total}} = 0.76 \times 10^{-3}.$$
Thus: 
\[ \frac{m_b}{d_m^{3/2} \sqrt{\Delta p}} = 0.182 \]

Assuming Frijlink transport formula, from graph, figure 1, which gives

\[ \frac{\Delta d}{\mu h I_b} = 8.4 \]

In the parameter \( \frac{\Delta d}{\mu h I_b} \), the slope is that one to the bottom shear only.

\[ \tau^2 = C_t \frac{h}{I_{\text{total}}} = C_b \frac{h}{I_b}, \quad \text{and} \quad c_b^2 = \frac{C_t^2 C_w^2 B}{C_w^2 B - 2C_t^2 \tau h} \]

\[ C_t^2 = \frac{\tau^2}{h I_{\text{total}}} = 587, \quad \text{or} \quad C_t = 24.2 \text{m}^3/\text{s}. \]

Wall friction \( C_w \).

Assume that the roughness factor, \( k \), for the walls =

\[ 5 \times 10^{-4} \text{ m}, \quad (a = \frac{k}{2} = 2.5 \times 10^{-4} \text{ m}). \]

\[ R_w = \frac{B}{2} = 0.15. \]

\[ R_w = \frac{0.15}{a} = \frac{0.15}{2.5 \times 10^{-4}} = 600. \]

\[ R_e = \frac{V R_w}{\nu} = \frac{0.232 \times 0.15}{10^{-6}} = 3.5 \times 10^4. \]

From the graph, according to Thijsse:

\[ C_w = 60 \text{ m}^3/\text{s}. \]

Thus:

\[ c_b^2 = \frac{587 \times 3600 \times 0.30}{(3600 \times 0.30) - (2 \times 587 \times 0.121)} = 676, \]

or

\[ c_b = 26 \text{ m}^3/\text{s}. \]
Energy slope due to bottom friction only:

\[ I_b = \frac{\bar{V}^2}{C_b^2 h} = 0.66 \times 10^{-3} \quad I_w = 0.10 \times 10^{-3} \]

Now \( \mu \) can be found from:

\[ \frac{\Delta \frac{d_m}{h \mu I_b}}{I_b} = 8.4 \quad \text{or} \quad \mu = 0.32 \]

For the preliminary calculations, \( \mu = 0.44 \) was found with the assumption of \( k = \frac{1}{3} \) ripple height. In reality, \( k \) is much bigger, even more than the ripple height, which results in a lower \( \mu \) value for the same transport conditions.

5.4. Test no. II. Deep water, with bars.

\[ \bar{Q} = 8.47 \times 10^{-3} \text{ m}^3/\text{s} \]

\[ \bar{h} = 0.119 \text{ m} \]

\[ \bar{V} = \frac{\bar{Q}}{\bar{h}} = 0.237 \text{ m/s} \]

\[ \frac{I_b}{I_{total}} = 1.34 \times 10^{-3} \]

Thus:

\[ \frac{T_b}{d_m^{3/2} \sqrt{\bar{g}}} = 0.185 \]

Slope due to the artificial roughness (\( C_D = 1.21 \), see 5.1)

\[ I_R = \frac{n^2 C_D b \bar{V}^2}{2 \bar{g}} = \frac{66.7 \times 1.21 \times 3 \times 10^{-3} (0.237)^2}{2 \times 9.81} = 0.69 \times 10^{-3} \]

\[ I_{total} = (1.34 - 0.69) \times 10^{-3} = 0.65 \times 10^{-3} \]

\[ C_t^2 = \frac{\bar{V}^2}{\bar{h} I_{total}} = 727, \text{ or } C_t = 27 \text{ m}^2/\text{s} \]

With \( C_w = 60 \text{ m}^2/\text{s} \):

\[ C_b^2 = 866, \text{ or } C_b = 29.4 \text{ m}^2/\text{s} \]

Slope due to bottom friction only:

\[ I_b = \frac{\bar{V}^2}{C_b^2 h} = 0.55 \times 10^{-3} \quad I_w = 0.10 \times 10^{-3} \]
From figure 1, when \( \frac{T_b}{d_m^{3/2} \sqrt{\Delta g}} = 0.185, \Delta d_m = 8.4, \) or \( \mu = 0.394. \)

5.5. Interpretation of the results of test no.'s I and II.

Test I and II were done with virtually the same flow conditions and the same rate of transport.

Nevertheless for test II a larger ripple factor must be introduced to bring the transport in accordance with Frijlinks formula. This increase in \( \mu \) is caused by the reduction of \( I_b \) which was measured (0.55x10\(^{-3}\) against 0.66x10\(^{-3}\)). Thus the bars influence the bottom roughness.

In the above case, the bottom roughness is reduced by the presence of the bars. This is in accordance with the observation that the ripples of test no. II were somewhat smaller than for for test no. I.

In a practical case where one wants to increase a model slope, by means of bars, from \( I_1 \) to \( I_2 \) (or increase the roughness from \( C_1 \) to \( C_2 \)) the slope due to the bars should be \( I_R = \eta (I_2 - I_1) \), where \( \eta \) is a correction factor to introduce the change of bottom roughness due to the presence of the bars.

For the particular conditions of test I and II is found from:

\[
\eta = \frac{I_R}{I_2 - I_1} = \frac{0.69}{1.24 - 0.66} = 1.19.
\]

The required base spacing will then be (see 4,3):

\[
r = \eta r_0 \left[ \frac{1}{c''^2} - \frac{1}{c'^2} \right]
\]

After elimination of the wall friction for test II(\( I_0 - I_w = (1.34 - 0.10)x10^{-3} = 1.24x10^{-3} \)) the Chezy roughness \( c' \) is found from:

\[
c'^2 = \frac{V^2}{(I_0 - I_w)h} = 380, \text{ or } c' = 19.5 \text{ m}^2/\text{s}.
\]

The overall roughness is thus increased from 26 m\(^{3/4}\)/s to 19.5 m\(^{3/4}\)/s!
5.6. Test no. III. Shallow water, no bars.

\[ \bar{Q} = 3.10 \times 10^{-3} \text{ m}^3/\text{s}. \quad T'_b = 16.2 \text{ N/hr}. \]
\[ \bar{h} = 0.062 \text{ m}. \]
\[ \bar{V} = \frac{\bar{Q}}{\bar{h} \cdot \bar{B}} = 0.167 \text{ m/s}. \]
\[ T_b = \frac{16.2}{\frac{3600 \times 0.3 \times 9.81 \times 1400}{\bar{h} \cdot \bar{B}}} = 1.09 \times 10^{-6} \text{ m}^2/\text{s}. \]
\[ I_E = I_{\text{total}} = 0.99 \times 10^{-3}. \]

Thus:
\[ \frac{T_b}{d_m^{3/2} \sqrt{\Delta \bar{g}}} = 0.044. \]

From figure 1, when \[ \frac{T_b}{d_m^{3/2} \sqrt{\Delta \bar{g}}} = 0.044. \]

In the same way as before, one finds: \[ \mu = \frac{A \cdot \bar{d}}{\mu h \bar{I}_b} = 12.6. \]
\[ C_t = 31.3 \text{ m}^{3/3}/\text{s}. \]

As before, \( C_w = 60 \) (independent of depth),
and \( C_p = 21.8 \text{ m}^{3/3}/\text{s}. \)

Thus:
\[ I_p = \frac{\bar{V}^2}{C_p^2 \bar{h}} = 0.94 \times 10^{-3} \quad \text{and} \quad I_w = 0.05 \times 10^{-3}, \]

and thus
\[ \mu = 0.292. \]

5.7. Test no. IV. Shallow water, with bars.

\[ \bar{Q} = 3.10 \times 10^{-3} \text{ m}^3/\text{s}. \quad T'_b = 16.2 \text{ N/hr}. \]
\[ \bar{h} = 0.074 \text{ m}. \]
\[ \bar{V} = \frac{\bar{Q}}{\bar{h} \cdot \bar{B}} = 0.140 \text{ m/s}. \]
\[ T_b = \frac{1.11 \times 10^{-6}}{\frac{3600 \times 0.3 \times 9.81 \times 1400}{\bar{h} \cdot \bar{B}}} = 0.06 \text{ m}^2/\text{s}. \]
\[ I_E = 1.37 \times 10^{-3}. \]

Thus:
\[ \frac{T_b}{d_m^{3/2} \sqrt{\Delta \bar{g}}} = 0.044. \]

Slope due to the artificial roughness \( (C_D = 1.47, \text{ see 5.1}) \)}
Thus:

\[ I_R = \frac{n' \cdot C_D \cdot bV^2}{2g} = \frac{66.7 \times 147 \times 0.3 \times 10^{-3} \cdot (0.140)^2}{2 \times 9.81} \]

\[ = 0.29 \times 10^{-3} \]

\[ I_{\text{total}} = (1.37 - 0.29) 	imes 10^{-3} = 1.08 \times 10^{-3} \]

Thus:

\[ C_t = 15.6 \text{ m}^3/\text{s}, \]

and

\[ C_b = 15.9 \text{ m}^3/\text{s}. \]

\[ I_b = \frac{V^2}{C_b \cdot h} = 1.05 \times 10^{-3} \text{ and } I_w = 0.03 \times 10^{-3}. \]

From fig. 1, \( \frac{\Delta d_m}{\mu h I_b} = 12.6 \) when \( \frac{T_b'}{d_m^{3/2} \sqrt{\Delta g}} = 0.044, \mu = 0.22 \).

5.8. Interpretation of the results from test no.'s III and IV.

For the shallow water, the opposite influence of the bars and the bottom roughness is found. The ripple factor is smaller in the case with bars or in other words with the same flow- and transport conditions, a greater bottom roughness (or a smaller \( C_b \) value) is obtained, when the bars are introduced.

A possible explanation for this unexpected increased bottom roughness can perhaps be found from the fact that without bars, the flow was slightly meandering, thus following a relatively deep channel. With bars, the meandering was stopped, and flow had to pass over more pronounced ripples.

In this case, the \( \eta \) value as defined under 5.5 becomes:

\[ \eta = \frac{0.29}{1.33 - 0.94} = 0.75 \text{ thus smaller than one!} \]

When the wall friction is eliminated again, the Chézy factor

\[ c' = \sqrt{V^2 (I_e - I_w h)} = 197 \]

or

\[ c' = 14 \text{ m}^3/\text{s}. \]
The overall roughness is thus increased from 21.8 m²/s to 14 m²/s.

5.9 Ripple sizes and celerities.

The photographically recorded ripple dimensions for test no.'s I and II are summarized in fig.'s 6, 7 and 8.

When the assumption is made that the shape of the ripples is triangular, the bedload can be calculated.

For test no. I.

Mean ripple height 4.0x10⁻² m. Width of channel B = 0.3 m.

" " celerity 1.76 m/hr.

\[ T_b = \frac{1}{3} \times 0.04 \times 0.3 \times 1.76 = 10.5 \times 10^{-3} \text{ m³/hr} \]

(1 litre mixture contains 6.55 N dry material)

\[ = 62 \text{ N/hr.} \]

Feeding rate was 66.6 N/hr.

For test no. II.

Mean ripple height 3.7x10⁻² m.

" " celerity 1.5 m/hr.

\[ T_b = \frac{1}{3} \times 0.037 \times 0.3 \times 1.5 = 8.35 \times 10^{-3} \text{ m³/hr} \]

= 54 N/hr.

Feeding rate was 67.6 N/hr.

However, in the latter case more transport in suspension (due to the bars) took place, which of course is not included in the 54 N/hr.

6. Conclusions and recommendations.

The following conclusions can be drawn as regards the influence of artificial bar resistance in a model with movable bed.

a) The bars influence the bottom configuration, and thus the bottom roughness or ripple sizes also.

Using the same flow rate Q, waterdepth h and transport T, both in the case with bars and without bars, for a waterdepth of approx. 10 cm the bottom roughness was reduced by the bars and for approx. 5 cm an increased bottom roughness was found.

b) A reduction of bottom roughness can partly be explained by the more rectangular velocity distribution as a result of the bar resistance and by the ability of the bars, to bring sediment in suspension in the vortex trails behind the bars,
c) In the case of the shallow water-depth, it was observed that a certain amount of meandering occurred in the case without bars, thus on the average a deeper channel with consequently lower resistance was available.

By putting in rods, the meandering was prevented and the flow was forced to go straighter. The increased bottom roughness may be explained by this phenomenon.

However, insufficient test results are available to draw a definite conclusion as regards to this.

d) For the waterdepths tested, the channel roughness can be increased by using bars.

For deep water, the Chezy coefficient was reduced by 0.6 and for shallow water by 0.64.

e) The method can be applied to models, provided the $\eta$ value for the major flow stages is known.

The required rod density is given by:

$$n' = \eta \frac{2g}{C_D b R} \left[ \frac{1}{C_1^2} - \frac{1}{C^2} \right]$$

When the depth is halved, $n'$ will be double, but in that case $\eta$ will reduced up to 35%, which for a great part compensates for the reduced depth, thus reducing the difference of $n'$ for different depths a great deal.

In view of the above conclusions, the following recommendations can be made:

a) More tests should be done, with different waterdepths, to ensure that the obtained results are representative.

Especially for shallow water, it should be tried to eliminate any difference in flow conditions (i.e. meandering) which may affect the results. For this purpose a thin model plate could subdivide the channel in the middle such as to reduce the channel width and any possible meandering.

b) Because there are so many variables, it seems better to test particular conditions for a certain model, rather then try to find a general rule. For instance in the case of a Niger model, a certain increase of roughness of the Benue is necessary.
The bar spacings can be calculated, when a value for $\eta$ is assumed, for each main river stage. When $n'$ is found, each river stage should be tested in two flumes with different widths and the correct values for $\eta$ determined from the test results. If necessary, $n'$ can be adjusted until the assumed value of $\eta$ coincides with the value found from the tests.
Nomenclature

\[ B \] = width of channel  
\[ b \] = diameter of roughness elements  
\[ C \] = Chezy resistance coefficient = 18 \log \frac{12 R}{K + 8/4}  
\[ C' \] = Resistance coefficient defined by \[ C' = \frac{V^2}{RI} \]  
\[ C_b \] = Chezy coefficient, assuming no wall friction  
\[ C_w \] = Chezy coefficient, assuming no bottom friction  
\[ C_t \] = a measure of combined wall and bottom resistance defined by  
\[ C_t^2 = \left[ \frac{C_b^2 C_w^2 B}{C_w^2 B + 2C_b^2 h} \right] \]  
\[ C_{gr} \] = 18 \log \frac{12h}{d_{90}} (grain roughness factor)  
\[ D \] = drag coefficient  
\[ d_m \] = mean diameter of the bed material  
\[ d_{90} \] = the diameter for which 90% of the material is smaller  
\[ g \] = acceleration of gravity  
\[ h \] = water depth (V-notch)  
\[ h \] = water depth  
\[ I_e \] = slope of energy line  
\[ I_b \] = slope due to bottom roughness only  
\[ I_w \] = slope due to wall roughness only  
\[ I_{\text{total}} = I_b + I_w \]  
\[ I_R \] = slope due to roughness elements only  
\[ k \] = roughness factor (or \( a = \frac{k}{2} \))  
\[ Q \] = discharge  
\[ R \] = hydraulic radius of the channel  
\[ R_b \] = hydraulic radius assuming no wall friction  
\[ R_w \] = hydraulic radius assuming no bottom friction  
\[ R_e \] = Reynolds' no. \( \frac{VR}{v} \)  
\[ T_b \] = total transport  
\[ T_b \] = transport per m width  
\[ V \] = velocity of flow  
\[ \delta \] = thickness of laminar sublayer  
\[ \Delta = \rho_s - \rho_w \]  
\[ \mu = \text{ripple factor} = \left[ \frac{C}{C_{gr}} \right]^{3/2} \]  
\[ \nu = \text{viscosity of water} \]  
\[ \rho_s \] = density of bed material  
\[ \rho_w \] = density of water
$\frac{\Delta d}{\mu R I}$

$T_b = 5 \sqrt{\frac{\mu g R I}{d}} e^{-0.27 \frac{\Delta d}{\mu R I}}$
TEST NO 1 13-4-62

I. BASE MATERIAL

II. TRANSPORTED MATERIAL

BAKELITE \( \sigma_5 = 1400 \text{ kg/m}^3 \)

I. \( d_{50} = 570 \mu \)
\( d_m = 540 \mu \) \( \sigma_5 = 1.38 \)
\( d_{90} = 760 \mu \)

II. \( d_{50} = 570 \mu \)
\( d_m = 540 \mu \) \( \sigma_5 = 1.30 \)
\( d_{90} = 740 \mu \)

SIZE DISTRIBUTION CURVES BAKELITE
(I) NO ARTIFICIAL ROUGHNESS

Mean Height = 4.0 cms
28 Readings

(I) WITH ARTIFICIAL ROUGHNESS

Mean Height = 3.7 cms
33 Readings
(I) NO ARTIFICIAL ROUGHNESS

MEAN LENGTH = 40.5 cms
17 READINGS

(II) WITH ARTIFICIAL ROUGHNESS

MEAN LENGTH = 31.0 cms
34 READINGS
(I) NO ARTIFICIAL ROUGHNESS

- Mean Celerity = 1.76 m/hr
- 23 Readings

(II) WITH ARTIFICIAL ROUGHNESS

- Mean Celerity = 1.50 m/hr
- 33 Readings

HISTOGRAM OF RIPPLE Celerity "DEEP" WATER

WATERLOOPKUNDIG LABORATORIUM

FIG. 8
Report no. 2

Tests with dune sand

Contents

1. Introduction ................................................................. 1
2. Test results ................................................................. 2
3. Calculations ................................................................. 3
4. Conclusions ................................................................. 7
5. Estimate of error in $\mu$ (test 4) ........................................ 8

Figures

1. Size distribution curves

Photographs

1. Ripple photo's test no. 1
2. Ripple photo's test no. 3
3. Ripple photo's test no. 4
The use of artificial roughness in movable bed models

Tests with dune sand

1. Introduction

The tests described in the following were the second in a series to find the effect of artificial roughness in movable bed models.

These tests were carried out in the same way as the first series except that in this case the bed material was dune sand whereas previously it was bakelite. A description of the apparatus and test procedure is given in the first report.

The tests performed using sand as bed material were:

Test 1. Nominal 10 cm waterdepth without artificial roughness
Test 2. " 10 cm " with " "
Test 3. " 5 cm " " "
Test 4. " 5 cm " without " "

These were carried out by Messrs.

S.R. GRAVELING
A.O. MAY
P. ROOVERS,

2. Test results

The average values are summarised in the table below.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Deep water</th>
<th>Shallow water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No rods test no.1, With rods test no.2, With rods test no.3, No rods test no.4</td>
<td></td>
</tr>
<tr>
<td>( Q ) (in ( 10^{-3} ) m(^3)/s)</td>
<td>12.3, 12.3</td>
<td>4.87, 4.87</td>
</tr>
<tr>
<td>( H ) (waterdepth in ( 10^{-2} ) m)</td>
<td>11.8, 11.8</td>
<td></td>
</tr>
<tr>
<td>( I_0 ) (energyslope)</td>
<td>1.7x10(^{-3}), 3.1x10(^{-3}), 2.9x10(^{-3}), 4.1x10(^{-3})</td>
<td></td>
</tr>
<tr>
<td>( T_t ) (total bedload in l/hr)</td>
<td>2.8, 2.8, 2.4, 2.8</td>
<td></td>
</tr>
<tr>
<td>( v ) measured velocity in ( 10^{-2} ) m/s</td>
<td>34.2, 29.2, 27.3, 25</td>
<td></td>
</tr>
<tr>
<td>( \bar{v} = \frac{Q}{b.H} ) in ( 10^{-2} ) m/s</td>
<td>34.5, 34.5, 28, 28</td>
<td></td>
</tr>
</tbody>
</table>

Size distribution curves of the feeding matering and the transported material are shown in fig. 1.

Photographs were taken at periods of 5 and 10 min. to obtain some value of the ripple sizes and propagation. Unfortunately photographs were not taken during the second test owing to the heavy rainfall at the time.

3. Calculations

The calculations are given in the table below. They were basically the same as for the first series of tests. The calculations for test No. 2 carry a small doubt because the recorded readings for the slope of the energy line were 1 cm less than shown (see Appendix 2). This original value, however, gave results which were highly improbable and it was thus concluded that an error of 1 cm had been made. This can happen if one reads at the 'wrong' end of a vernier scale, which on a rainy day and with an instrument not clearly marked, is quite possible.
<table>
<thead>
<tr>
<th>Calculation formula</th>
<th>Test No. 1</th>
<th>Nominal 10 cm</th>
<th>Test No. 2</th>
<th>Nominal 10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no bars</td>
<td></td>
<td>with bars</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dune sand, $\rho_s = 2650 \text{ kg/m}^3$</td>
<td>Dune sand, $\rho_s = 2650 \text{ kg/m}^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d_m = 210 \mu$, $d_{90} = 300 \mu$</td>
<td>$d_m = 210 \mu$, $d_{90} = 300 \mu$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q = 12.3 \text{ l/sec}$</td>
<td>$Q = 12.3 \text{ l/sec}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I_e = 1.7 \times 10^{-3}$</td>
<td>$I_e = 3.1 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$h = 11.8 \text{ cm}$</td>
<td>$h = 11.8 \text{ cm}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T'_b = 4.4 \text{ l/hr (wet)}$</td>
<td>$T'_b = 4.4 \text{ l/hr (wet)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$= 2.8 \text{ l/hr (dry)}$</td>
<td>$= 2.8 \text{ l/hr (dry)}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurements</th>
<th></th>
<th>Neglecting wall roughness</th>
<th>Neglecting wall roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{\frac{Q}{Bh \cdot \text{hile}}} = \frac{V}{\text{hile}}$</td>
<td></td>
<td>$V = \frac{0.0123}{0.3 \times 0.118} = 0.345 \text{ m/s}$</td>
<td>$V = \frac{0.0123}{0.3 \times 0.118} = 0.345 \text{ m/s}$</td>
</tr>
<tr>
<td>$C_r = \frac{Q}{Bh \cdot \text{hile}} = \frac{V}{\text{hile}}$</td>
<td></td>
<td>$C' = \frac{0.345}{\sqrt{0.118 \times 1.7 \times 10^{-3}}} = 24.6 \text{ m}^3/\text{s}$</td>
<td>$C' = \frac{0.345}{\sqrt{0.118 \times 1.7 \times 10^{-3}}} = 18 \text{ m}^3/\text{s}$</td>
</tr>
<tr>
<td>$C_{gr} = 18 \log \left( \frac{12h}{d_{90}} \right)$</td>
<td></td>
<td>$C_{gr} = 18 \log \left( \frac{12 \times 0.118}{3 \times 10^{-4}} \right) = 66 \text{ m}^3/\text{s}$</td>
<td>$C_{gr} = 66 \text{ m}^3/\text{s}$</td>
</tr>
<tr>
<td>$I_e^2 = I_R + I_b$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_r = c_t = c' = 24.6 \text{ m}^3/\text{s}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neglecting wall roughness</th>
<th>Neglecting wall roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_R = \frac{3}{2} \times 20 \times 1.20 \times 3 \times 10^{-3} \times 0.345^2$</td>
<td>$I_R = \frac{3}{2} \times 20 \times 1.20 \times 3 \times 10^{-3} \times 0.345^2$</td>
</tr>
<tr>
<td>$= 1.45 \times 10^{-3}$</td>
<td>$= 1.45 \times 10^{-3}$</td>
</tr>
<tr>
<td>$I_b = (3.1 - 1.45) \times 10^{-3} = 1.65 \times 10^{-3}$</td>
<td>$I_b = (3.1 - 1.45) \times 10^{-3} = 1.65 \times 10^{-3}$</td>
</tr>
<tr>
<td>$C_b = C_t = \frac{0.345}{\sqrt{0.118 \times 1.7 \times 10^{-3}}} = 24.6 \text{ m}^3/\text{s}$</td>
<td>$C_b = C_t = \frac{0.345}{\sqrt{0.118 \times 1.7 \times 10^{-3}}} = 24.6 \text{ m}^3/\text{s}$</td>
</tr>
<tr>
<td>$\mu = \left( \frac{24.6}{66} \right)^{3/2} = 0.23$</td>
<td>$\mu = \left( \frac{24.6}{66} \right)^{3/2} = 0.23$</td>
</tr>
<tr>
<td>$\mu = \frac{4.35 \times 10^{-5}}{1.7 \times 10^{-3} \times 0.118} = 0.22$</td>
<td>$\mu = \frac{4.35 \times 10^{-5}}{1.7 \times 10^{-3} \times 0.118} = 0.224$</td>
</tr>
<tr>
<td>Calculation formula</td>
<td>Test No. 1 - (con.)</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>( C_v = 18 \log \frac{12xB/2}{K} ), where ( K ) is assumed ( = 5 \times 10^4 ) m</td>
<td>( C_w = 18 \log \frac{12x0.3/2}{5 \times 10^{-4}} = 64 \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>( C_t = \frac{12x0.3}{2} x 0.30 )</td>
<td>( C_t = 24.6 \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>( I_w = \frac{\sqrt{C_v}}{C_w^{2/3}} \times 0.345 \times \frac{2}{2} = 0.2 \times 10^{-3} )</td>
<td>( I_w = 0.2 \times 10^{-3} )</td>
</tr>
<tr>
<td>( I_b = I_e - I_w = (1.7 - 0.2) \times 10^{-3} = 1.5 \times 10^{-3} )</td>
<td>( I_b = I_e - I_w = (3.1 - 0.2 - 1.45) \times 10^{-3} = 1.45 \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_b = 26.2 \text{ m}^2/\text{s} )</td>
<td>( C_b = \frac{0.345}{\sqrt{0.118 \times 1.65 \times 10^{-3}}} = 26.3 \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>( \mu = \left( \frac{C_b}{C_{gr}} \right)^{3/2} )</td>
<td>( \mu = \left( \frac{26.2}{66} \right)^{3/2} = 0.25 )</td>
</tr>
<tr>
<td>Calculations of ripple heights</td>
<td>Neglecting wall roughness</td>
</tr>
<tr>
<td>( \frac{1}{C_{ripple}} = \frac{1}{C_b^2} - \frac{1}{C_{gr}^2} )</td>
<td>( C_{ripple} = \frac{24.6 \times 66}{\sqrt{66^2 - 24.6^2}} = 25.6 \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>( C_{ripple} = \frac{C_b}{\sqrt{C_{gr}^2 - C_b^2}} )</td>
<td>( C_{ripple} = \frac{26.2 \times 66}{\sqrt{66^2 - 26.2^2}} = 28.5 \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>( \mu = \frac{\mu h_i}{h_i e} )</td>
<td>( \mu = \frac{4.35 \times 10^{-5}}{0.118 \times 1.5 \times 10^{-3}} = 0.25 )</td>
</tr>
<tr>
<td>( 1/C_{ripple} = 1/C_b^2 - 1/C_{gr}^2 )</td>
<td>( 1/C_{ripple} = 1/C_b^2 - 1/C_{gr}^2 )</td>
</tr>
<tr>
<td>( K \cdot \text{ripple height} )</td>
<td>( K \cdot \text{ripple height} )</td>
</tr>
<tr>
<td>( K \cdot \text{ripple height} = \frac{18 \log \frac{12L}{K}}{A_{ripple}} )</td>
<td>( K \cdot \text{ripple height} = \frac{18 \log \frac{12L}{K}}{A_{ripple}} )</td>
</tr>
<tr>
<td>( K \cdot \text{ripple height} = \frac{18 \log \frac{12L}{K}}{A_{ripple}} )</td>
<td>( K \cdot \text{ripple height} = \frac{18 \log \frac{12L}{K}}{A_{ripple}} )</td>
</tr>
<tr>
<td>Calculation formula</td>
<td>Test No. 3 Nominal 5 cm with bars</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Formula as given in Appendix 10.</td>
<td>Dune sand, ( \rho_s = 2650 \text{ kg/m}^3 )</td>
</tr>
<tr>
<td>Measurements</td>
<td>( d_m = 210 \mu, d_{90} = 300 \mu )</td>
</tr>
<tr>
<td>( Q = 4.87 \text{ l/sec} )</td>
<td>( Q = 4.87 \text{ l/sec} )</td>
</tr>
<tr>
<td>( I_e = 2.9x10^{-3} \text{ l} )</td>
<td>( I_e = 2.9x10^{-3} \text{ l} )</td>
</tr>
<tr>
<td>( h = 5.76 \text{ cm} )</td>
<td>( h = 5.76 \text{ cm} )</td>
</tr>
<tr>
<td>( T_b = 3.8 \text{ l/hr (wet)} )</td>
<td>( T_b = 3.8 \text{ l/hr (wet)} )</td>
</tr>
<tr>
<td>( = 2.4 \text{ l/hr (dry)} )</td>
<td>( = 2.4 \text{ l/hr (dry)} )</td>
</tr>
<tr>
<td>Neglecting wall roughness</td>
<td>Neglecting wall roughness</td>
</tr>
<tr>
<td>( v = \frac{0.00487}{0.3x0.0576} = 0.28 \text{ m/s} )</td>
<td>( v = \frac{0.00487}{0.3x0.0576} = 0.28 \text{ m/s} )</td>
</tr>
<tr>
<td>( C_t = \frac{0.28}{\sqrt{0.0576x2.9x10^{-3}}} = 21.7 \text{ m}^3/\text{s} )</td>
<td>( C_t = \frac{0.28}{\sqrt{0.0583x4.1x10^{-3}}} = 18 \text{ m}^3/\text{s} )</td>
</tr>
<tr>
<td>( C_{gr} = 18 \log \frac{12x0.0576}{3x10^{-4}} = 60.5 \text{ m}^2/\text{s} )</td>
<td>( C_{gr} = 60.5 \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td>( I_R = \frac{4x20x1.30x3x10^{-3}}{0.3} \times \frac{0.28^2}{4.81} )</td>
<td>( I_R = (2.9-1)x10^{-3} = 1.9x10^{-3} )</td>
</tr>
<tr>
<td>( = 1x10^{-3} )</td>
<td>( = 1x10^{-3} )</td>
</tr>
<tr>
<td>( C_b = \frac{0.28}{\sqrt{0.0576x1.9x10^{-3}}} = 27 \text{ m}^3/\text{s} )</td>
<td>( C_b = C_t = C_t = 18 \text{ m}^3/\text{s} )</td>
</tr>
<tr>
<td>( \mu = \left( \frac{27}{60.5} \right)^{3/2} = 0.30 )</td>
<td>( \mu = \left( \frac{18}{60.5} \right)^{3/2} = 0.16 )</td>
</tr>
<tr>
<td>( \mu = \frac{4.15x10^{-5}}{0.0576x1.9x10^{-3}} = 0.38 )</td>
<td>( \mu = \frac{4.35x10^{-5}}{0.0583x4.1x10^{-3}} = 0.18 )</td>
</tr>
<tr>
<td>Calculation formula</td>
<td>Test No. 3 - (con.)</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td><strong>Formula as given in Appendix 11</strong></td>
<td><strong>Considering wall roughness</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Test No. 3 - (con.)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Neglecting wall roughness</strong></td>
</tr>
<tr>
<td>Calculation of ripple heights</td>
<td><strong>Neglecting wall roughness</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Giving K = 1.65 cm</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Giving K = 1.2 cm</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Calculation of ( \eta )</strong></td>
</tr>
<tr>
<td></td>
<td>[ \eta = \frac{1}{2.7-3.9} = 0.83 ]</td>
</tr>
</tbody>
</table>

**Test No. 3 - (con.)**

Formula as given in Appendix 11:

- \( C_w = 64 \text{ m}^2/\text{s} \)
- \( C_t = \frac{0.28}{\sqrt{0.0576 \times 1.9 \times 10^{-3}}} = 26.7 \text{ m}^2/\text{s} \)
- \( I_w = \frac{V^2}{C_w^2 B} = \frac{0.28^2}{64^2 \times 30/2} = 0.2 \times 10^{-3} \)
- \( I_b = I_e - I_w - I_R = (2.9 - 0.2 - 1) \times 10^{-3} = 1.7 \times 10^{-3} \)
- \( C_b = \frac{0.28}{\sqrt{0.0576 \times 1.7 \times 10^{-3}}} = 28 \frac{m}{s} \)
- \( \mu = (\frac{0.28}{0.5})^{3/2} = 0.32 \)
- \( \mu = \frac{4.15 \times 10^{-5}}{0.0576 \times 1.7 \times 10^{-5}} = 0.43 \)

**Test No. 4 - (con.)**

Formula as given in Appendix 11:

- \( C_w = 64 \text{ m}^2/\text{s} \)
- \( C_t = 18 \text{ m}^2/\text{s} \)
- \( C_b = \frac{18^2 \times 64^2 \times 30^2}{64^2 \times 30^2 - 2 \times 18^2 \times 0.0583} = 18.3 \text{ m}^3/\text{s} \)
- \( I_w = 0.2 \times 10^{-3} \)
- \( I_b = I_e - I_w = (4.1 - 0.2) \times 10^{-3} = 3.9 \times 10^{-3} \)
- \( C_b = 18.3 \text{ m}^3/\text{s} \)
- \( \mu = (\frac{18.3}{0.5})^{3/2} = 0.17 \)
- \( \mu = \frac{4.35 \times 10^{-5}}{0.0583 \times 3 \times 9 \times 10^{-3}} = 0.19 \)
4. Conclusions and recommendations

From the results of the tests the following can be said.

a) There is a good agreement of the average velocity, found by measurement of discharge and waterdepth, with the velocity measured by the current meter, except in test No. 2, where the difference is about 15%.

b) The measured quantity of the material leaving the flume and that introduced to the flume were practically the same.

c) Comparison of photographs those for tests 3 and 4 (5 cm depth) shows that, without artificial roughness, the ripples are very unregular and high, but that with artificial roughness they are much more regular and lower.

d) The influence of the wall roughness of the flume is small, having about 5% effect on $C$ values and 5-10% on $\mu$ values.

e) Introducing artificial roughness by bars does not necessarily increase the total roughness because the bars cause much more regular and lower ripples.

For the 10 cm tests:
The Chezy coefficient $C' (= \frac{C}{\sqrt{R}})$ changes from 24.6 to 18 m$^{3}$/sec when bars are introduced; $C_b$ changes only from 26.2 to 26.3 m$^{3}$/sec.

For the 5 cm tests:
Here $C'$ increases from 18 to 21.7 m$^{3}$/sec, $C_t$ increases from 18 to 26.7 m$^{3}$/sec and $C_b$ increases from 18.3 to 28 m$^{3}$/sec.
The above results suggest that the artificial roughness has more effect on the bed formation at small water depths than at large ones.

f) Introduction of artificial roughness causes the following effects on the ripple factor:
For 5 cm: There is an increase from 0.19 to 0.43.
For 10 cm: There is little change i.e. 0.25 to 0.26.

g) A good agreement exists between values of $\mu$ calculated from Frijlink's transport formula and values of $\mu = \left(\frac{C_t}{C_b} \right)^{1/2}$.

For the 5 cm test with artificial roughness the difference was about 25%. For the rest, differences were within 10%.

h) An estimate of the 'probable error' involved in making the calculations shows that the error is not likely to be greater than about 10%.
5. Estimate of error in \( \mu \) (test 4)

The value of \( \mu \) was determined from

\[
\psi = \frac{\mu h}{\Delta d}
\]

where \( \psi \) is determined from Frijlinks \( \psi - \beta \) relation.

\[
\beta = \frac{T_b}{(d^3 g \Delta)^{1/3}}
\]

In the neighbourhood of the test values of \( \psi, \psi \) varies with the \( 1/3 \) power of \( \beta \). Thus

\[
\mu \sim T^{1/3} \Delta^{5/6} \frac{d^{1/3}}{h^{-1} I^{-1}}.
\]

The error in \( T \) was estimated to be 10\%, that in \( \Delta \) 2\% and the error in \( d \) 5\%.

The error in \( h \) and \( I \) could be estimated from the measurements.

The standard error in the mean value is

\[
s = \sqrt{\frac{\varepsilon(h-\bar{h})^2}{n(n-1)}}
\]

Where \( h \) is the individual reading, \( \bar{h} \) is the mean depth and \( n \) is the number of observations. \( s \) has been found for both upstream and downstream measurements.

For upstream

\[
\varepsilon(h-\bar{h})^2 = 19.8 \text{ cm}^2 \quad n = 30 \quad \bar{h} = 6.08
\]

\[
s = 0.15 \text{ cm}.
\]

For downstream

\[
\varepsilon(h-\bar{h}) = 29.3 \text{ cm}^2 \quad n = 30 \quad \bar{h} = 5.83 \text{ cm}
\]

\[
s = 0.18 \text{ cm}
\]

So the standard error in the mean depth from both upstream and downstream measurements together amounts to \( s = 0.2 \text{ cm} \).

Standard error with slope \( I \)

\[
\varepsilon(I-\bar{I})^2 = 48 \times 10^{-8} \quad n = 10 \quad \bar{I} = 4.1 \times 10^{-3}
\]

\[
s = 0.07 \times 10^{-3}. \text{ Together with an error in the pitot tube orientation. } \delta_1 = 0.10 \times 10^{-3}.
\]
Summarized

\[
\bar{T} = 2.8 \text{ l/hr} \quad \delta_T = 0.28 \text{ l/hr}
\]

\[
\bar{\Delta} = 1.65 \quad \delta_{\Delta} = 0.03
\]

\[
\bar{d} = 210 \mu \quad \delta_{d} = 10 \mu
\]

\[
\bar{h} = 5.95 \text{ cm} \quad \delta_{h} = 0.2 \text{ cm}
\]

\[
\bar{I} = 4.1 \times 10^{-3} \quad \delta_{I} = 0.10 \times 10^{-3}
\]

The maximum error is given by:

\[
\frac{\delta \mu}{\mu} = \frac{1}{3} \frac{\delta T}{T} + \frac{5}{6} \frac{\delta \Delta}{\Delta} + \frac{1}{2} \frac{\delta d}{d} + \frac{\delta h}{h} + \frac{\delta I}{I} = 8.5 \%
\]

For the test with bars the error in \( \mu \) will be larger as a consequence from the error in determining \( I_{\text{bars}} \).
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