International Standard 4369

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Measurement of liquid flow in open channels — Moving-boat method

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Foreword

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Measurement of liquid flow in open channels — Moving-boat method

1 Scope and field of application

This International Standard specifies methods for measuring discharge in large rivers and estuaries by the moving-boat technique. In the following sections procedures applicable to this method and the general requirements of equipment are covered. A complete facsimile example of computation of a moving boat measurement is given in the annexes.

2 References

ISO 748, *Liquid flow measurement in open channels — Velocity area methods*.

ISO 772, *Liquid flow measurement in open channels — Vocabulary and symbols*.

ISO 3454, *Liquid flow measurement in open channels — Sounding and suspension equipment*.

ISO 4366, *Liquid flow measurement in open channels — Echo sounders*.

ISO 5168, *Calculation of the uncertainty of a measurement of flowrate*.[1]

3 Definitions

For the purpose of this International Standard the definitions given in ISO 772 apply.

4 Units of measurement

Thd units of measurement used in this International Standard are SI units.

5 General

Frequently, on large rivers and estuaries, conventional methods of measuring discharge by current meters are difficult and involve costly and tedious procedures.

This is particularly true at remote sites where no facilities exist, or during floods when facilities may be inundated or inaccessible.

In those cases where unsteady flow conditions require that measurement be made as rapidly as possible, the moving-boat technique is applicable. It requires no fixed facilities and it lends itself to the use of alternate sites.

The moving-boat technique uses a velocity-area method of determining discharge. The technique requires that the following information be obtained :

a) location of observation points across the stream with reference to the distance from an initial point;

b) stream depth, d, at each observation point;

c) stream velocity, v, perpendicular to the cross section at each observation point.

The principal difference between a conventional measurement and the moving-boat measurement is in the method of data collection. The mean velocity in the segments of a cross-section of the stream in the case of a conventional technique is determined by point velocities or an integrated mean velocity in the vertical. The moving-boat technique measures the velocity over the width of a segment by suspending the current meter at a constant depth during the traverse of the boat across the stream. The measured velocity and the additional information of the depth sounding gives the required data for determining the discharge.

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[1] At present at the stage of draft.

6 Principle of the moving-boat method

The moving-boat measurement is made by traversing the stream along a preselected path that is generally normal to the streamflow (see figure 1). During the traverse an echo sounder records the geometry of the cross-section and a continuously operating current meter senses the combined stream and boat velocities.

A third set of data needed is obtained either by measuring at intervals the angle between the current meter, which aligns itself in a direction parallel to the movement of the water past it, and the preselected path or by measuring the distance to a fixed point on the bank.

The velocity measurement observed at each of the observation points in the cross-section (v_v in figure 2) is the velocity of water past the current meter resulting from both stream flow and boat movement. It is the vector sum of the velocity of water with respect to the stream bed (v) and the velocity of the boat with respect to the stream bed (v_b).

The sampling data recorded at each observation point provide the necessary information to determine the velocity of the stream. There are two methods to obtain this velocity, referred to as method 1 and method 2.

Method 1 consists of measuring the angle α between the selected path of the boat and a vertical vane which aligns itself in a direction parallel to the movement of the water past it. An angle indicator attached to the vane assembly indicates angle α.

Method 2 consists of measuring the distance from the observation points to a fixed point on the bank from which the width of the traversed segment can be determined along with the simultaneous measurement of time. From these data, the velocity component of the boat, v_b, can be computed and by means of the measurement of total velocity, v_v, the velocity component, v, of the stream perpendicular to the selected boat path is determined.

The reading from the rate indicator unit in pulses per second is used in conjunction with a calibration table to obtain the vector magnitude v_v.

Normally, data are collected at 30 or 40 observation points in the cross-section for each run. Where practicable, automatic and simultaneous readings of all required parameters may be recorded.

6.1 Determination of stream velocity

By method 1 the stream velocity v, perpendicular to the boat path (true course) at each observation point 1, 2, 3, . . ., can be determined from the relationship

$$v = v_v \sin \alpha \qquad \ldots (1)$$

The solution of equation (1) yields an answer which represents that component of the stream velocity which is perpendicular to the true course even though the direction of flow may not be perpendicular.

By method 2 the stream velocity can be determined from

$$v = \sqrt{v_v^2 - v_b^2} \qquad \ldots (2)$$

where v_b is obtained from

$$v_b = \frac{l_i - l_{(i-1)}}{t_i} \qquad \ldots (3)$$

(see figure 3)

where

i is the observation point order;

l_i is the distance from observation point i to a fixed point on the bank;

t_i is the time required to traverse the width of a segment.

6.2 Determination of distance between observation points

From the vector diagram, (see figure 2) it can be seen that

$$\Delta l_b = \int v_v \cos \alpha \, dt \qquad \ldots (4)$$

where Δl_b is the distance which the boat has travelled along the true course between two consecutive observation points, provided the stream velocity is perpendicular to the path.

Where the velocity is not perpendicular, an adjustment is required as explained in 10.3.

If it is assumed that α is approximately uniform over the relatively short distance which makes up any one increment, then it may be treated as a constant.

Therefore applying method 1, equation (4) becomes

$$\Delta l_b \approx \cos \alpha \int v_v \, dt \qquad \ldots (5)$$

Now

$$\int v_v \, dt = \Delta l_v$$

where Δl_v is the relative distance through the water between two consecutive observation points as represented by the output from the rate indicator and counter.

Therefore for the ith relative distance

$$\Delta l_{b_i} \approx \Delta l_{v_i} \cos \alpha_i \qquad \ldots (6)$$

the total width, B, of the cross sectional area is

$$B = \sum_{i=1}^{i=m} \Delta l_{b_i} \approx \sum_{i=1}^{i=m} \Delta l_{v_i} \cos \alpha_i \qquad \ldots (7)$$

If method 2 is applied, then the width of the interval between observation points should be computed as the difference between successive distance measurements from a fixed point on one of the banks as shown in equation (3).

6.3 Determination of stream depth

The stream depth at each observation point should be obtained by adding the transducer depth to the depth from the echo sounder chart, unless the transducer is set to read total depth.

7 Limitations

The method is normally employed on rivers over 300 m wide and over 2 m in depth.

The minimum width which is required depends on the number of segments into which the cross-section is divided and the minimum time to pass these segments to obtain a sufficiently accurate measurement.

The number of segments should be at least 25.

The width to be taken for each segment depends on the accuracy with which the velocity in each segment can be measured. The interval between two observation points should be sufficient to allow the observer to read the instruments and record the results. The minimum speed of the boat should be such as to ensure that the boat may traverse the section in a straight line. For the best results this speed should be of the same order as the velocity of the stream.

The river should be of sufficient depth to allow for the draught of the boat and the requirement of easy manœuvring during the traverse of the cross-section. Shallow locations may cause damage to the instruments as the current meter and/or vane extend about 1 m below the boat.

The stream should not have an under-current, as can be the case in tidal-flow, where the direction is opposite to the flow in which the velocity is measured. In such cases the velocity distribution in the vertical is unknown and the mean velocity cannot be satisfactorily correlated to the measured velocity.

During the time that the boat traverses the stream the discharge should not change to such an extent that an unreliable measurement is obtained. For unsteady flow conditions on tidal streams, it will normally be desirable not to average the results from a series of runs, but rather to keep them separate so as to better define the discharge cycle (see figure 4).

8 Equipment

8.1 General

The equipment required is similar no matter which of the two methods is used (see clause 6).

Essentials of the equipment required for both methods are given below. A more detailed description of the equipment is dealt with in annex A.

8.2 Boat

An easily manœuvrable boat which is sufficiently stable for the stream in which it is to be used is required.

8.3 Vane and angle indicator (method 1)

A vane with indicating mechanism should be mounted on a suitable part of the boat, generally the bow. The angle between the direction of the vane and the true course of the boat should be indicated on a dial by the pointer mounted in line with the vane. A sighting device attached to the free swivelling dial provides a means of aligning the index point on the dial with the true course. The dial should be calibrated in degrees (from 0 to 90°) on both sides of its index point.

8.4 Current meter

The current meter should preferably be a component propeller type with a body which should be, in the case of method 1, adapted for mounting on the leading edge of the vane. If method 2 is applied, the current meter with its sounding weight should be suspended on a cable from the boat. The requirements for this suspension equipment should conform to ISO 3454 on sounding and suspension equipment.

8.5 Pulse rate indicator and counter

The revolutions of the current meter are transmitted as electrical pulses which should be displayed on a counter or converted via an electronic assembly to a velocity display.

In the first case, the pulses are converted to velocity by the use of a current meter rating table.

If method 1 is applied, the counting unit should have provision to preset the number of electronically counted pulses. An audible signal is generated when the preset number is reached and the echo sounder chart is automatically marked. The counter should automatically reset itself before repeating the process. A sketch and description of the rate indicator and counter are given in figure 5.

8.6 Distance measurement (method 2)

To locate the observation points in the cross-section, the distance should be measured from each point to a fixed position on the embankment. The distance measurement can be performed optically for example by a range finder or by electronic equipment (for example a radiolog).

The distance measuring device should have a (relay) connection with the echo sounder so that at each observation point a vertical line marking can be triggered on the sounder stripchart (automatically or by hand).

8.7 Echo sounder

A (portable) echo sounder should be used to provide a continuous stripchart of the depth profile of the cross-section between the two floats. The echo sounder should have the facility of a relay connection with the rate indicator and counter or the distance meter to trigger vertical line markings on the sounder chart at each observation point. The echo sounder should conform to ISO 4366.

9 Measurement procedures

Procedures for a moving-boat measurement should include selection and preparation of a suitable measuring site, preparation and assembly of the equipment used for the measurement and a selection of settings for the instruments used to collect the data.

9.1 Selection of the site

The measuring site should be selected so that substantially uniform flow can be expected. This means that streamlines are as parallel as possible and that the bed shows no sharp discontinuities.

9.2 Preparation of the site

Some preparation of the site is required prior to starting a series of moving-boat measurements.

9.2.1 A path for the boat to travel should be selected which is as nearly perpendicular to the flow direction as possible. This path should be marked by two clearly visible range markers placed on each bank. The colour of these markers should contrast sharply with the background. Spacing between the markers is dependent upon the length of the path. Approximately 30 m of spacing is required for each 300 m of path length.

9.2.2 Anchored floats to mark the beginning and ending points of the measurement should be placed in the stream 12 to 15 m from each shore along the selected path (see figure 1). In making a traverse, this distance is needed for manœuvring the boat when entering or leaving the path. The floats should be placed so that the depth of water in their vicinity is always greater than 1 m (vane or current meter depth).

It is preferable to offset the floats about 3 to 6 m upstream of the line of the boat path in order that they do not interfere with the approaching boat.

9.2.3 The width of the stream may be measured by triangulation, stadia or other methods and the exact locations of the floats determined. The distance of the floats to the edge of the water should be measured (for example with a tape measure), and should be noted in the main part of the measurement notes for use in the computation of the measurement. When method 1 is used it is desirable to have permanent cross-section markers so that the true width may be conveniently computed by measuring from the markers to the water's edge. (If method 2 is used the distance between the markers should be checked each time a measurement is made thus providing a calibration check on the distance measuring device).

9.3 Function of the crew members

Three experienced crew members are usually necessary for making a moving-boat discharge measurement.

For method 1 they include a boat operator, an angle observer and a notekeeper; for method 2 a boat operator, an observer for the pulses of the current meter, who is also notekeeper, and a distance observer.

Before crew members begin making discharge measurements by the moving-boat method it is important that they develop a high degree of proficiency in all aspects of the technique.

A short description of the function of the crew members follows below. A more detailed description is given in annex A.

a) The notekeeper should be the person responsible for both the preparation and execution of the measurement. He should also report the results of the measured data (see annex B).

b) The boat operator should be familiar with the measuring site and should take care that the boat remains on line as nearly as possible throughout the traverse of the cross-section.

c) The angle observer (method 1) should read the angle formed by the vane with respect to the true course and report the result to the notekeeper.

d) The distance observer (method 2) should read the distance to one of the markers on the bank using optical or electronic equipment. He should mark the observation points on the stripchart of the echo sounder if this is done manually.

If automatic, simultaneous recording is used the number of crew members may be reduced to two.

10 Computation of discharge

10.1 General

Theoretically the discharge is given by

$$Q = A \int v(x,y)\, \mathrm{d}x\mathrm{d}y$$

where

Q is the true discharge;

A is the cross-sectional area;

$v(x,y)$ is the velocity field over width and depth.

In practice the integral is usually approximated by the summation

$$Q_\mathrm{m} = \sum_{i=1}^{i=m} b_\mathrm{i} d_\mathrm{i} \bar{v}_\mathrm{i} \qquad \ldots (8)$$

where

Q_m is the calculated discharge;

b_i is the width of the ith segment;

d_i is the depth of the ith segment;

$\bar{v}_i$ is the mean velocity in the ith segment;

m is the number of segments.

The stream discharge is then the summation of the products of the segment areas of the stream cross-section and their respective mean velocities.

The moving-boat measurement utilizes the mid-section method of computing discharge. This method assumes that the mean velocity at the middle of each segment represents the mean velocity in the segment. The area extends laterally from half the distance from the preceding meter location to half the distance to the following and vertically from the water surface to the sounded bed (see ISO 748).

10.2 Method of computation

In figure 3, a definition sketch of the midsection method has been superimposed over a facsimile of a cross-section profile from an echo sounder chart. The cross-section is defined by depths at locations 1, 2, 3, . . . , *n*, which were marked during the measurement on the echo-sounder chart.

According to the midsection method, the partial discharge is computed for any section at location *i* as

$$q_i = v_i \left[\frac{l_{(i+1)} - l_{(i-1)}}{2} \right] d_i \qquad \dots (9)$$

where

q_i is the unadjusted discharge through section i;

v_i is the sampled velocity at location i;

$l_{(i-1)}$ is the distance from initial point to the preceding location;

$l_{(i+1)}$ is the distance from initial point to the next location;

d_i is the depth of water at location i.

The stream velocity should be determined for location *i* either by equation (1) when method 1 is applied or by equation (2) for method 2. For further details see tables 1 and 2, where a complete measurement has been computed for method 1 and method 2 respectively.

The distance from the initial point (marker on the bank) to the observation point where the data are collected is the summation of the cumulative distance from the meter locations to the float, the distance from the float to the edge of the water and the distance from the edge of the water to the marker (see figure 3). These last two distances are measured separately for each bank. The distances are defined as follows :

l_1 = distance from initial point (marker) to edge of water

$l_2 = l_1$ + measured distance to float from edge of water

$l_3 = l_2 + \Delta l_{b_3}$

$l_4 = l_3 + \Delta l_{b_4}$

$l_{(n-1)} = l_{(n-2)} + \Delta l_{b_{(n-1)}}$

$l_n = l_{(n-1)}$ + measured distance from float to edge of water

$l_{(n+1)} = l_n$ + distance to final point (marker)

In the above, Δl_{b_i} is the distance from the meter location to the preceding one as determined according to method 1.

For method 2 the distances l_i to the marker are measured directly. Each of the segment widths represents the distance that extends laterally from half the distance from the preceding meter location ($i - 1$) to half the distance to the next, ($i + 1$). For example the width of the segment *i* equals

$$b_i = \frac{l_{(i+1)} - l_{(i-1)}}{2} \qquad \dots (10)$$

The stream depth at each measuring point in the cross-section is obtained by adding the transducer depth to each of the depth readings recorded on the echo sounder chart at the sampling locations.

Depending on the apparatus used, this addition can be done automatically.

The individual segment areas are obtained by multiplying the width as obtained from equation (10), by the depth at the measuring point.

The incremental areas are then summed to provide the total unadjusted area for the measurement.

According to equation (9), the (unadjusted) discharge through one of the segments is obtained by multiplying the unadjusted area and the measured velocity at the observation point. These values should be summed to provide the total (unadjusted) discharge for the measurement. The brackets refer to method 1.

10.3 Correction for width in the case of oblique flow (method 1)

10.3.1 General

There may be circumstances when a measurement site must be chosen in which the flow is not normal to the cross-section. Then if method 1 is applied, the width of the segments should be computed from the relationship expressed by equation (6).

$$\Delta l_{b_i} \approx l_{v_i} \Delta \cos \alpha_i$$

This equation is based on the assumption that a right triangle relationship exists between the velocity vectors involved.

If the flow is not normal to the cross-section, this situation does not exist and the use of the equation can result in a computed width that is too large or too small, depending on whether the vector quantity representing the oblique flow has a component that is opposed to, or in the direction of, that of the boat (see figure 6).

Where method 2 is applied, no correction for width is needed as the distances are measured directly.

The component of the flow normal to the cross-section is not influenced by the boat velocity component as long as the boat path is parallel to the cross-section.

To compensate for minor deviations of the direction of flow or the deviations between the boat path and the cross-section, an equal number of runs should be taken in both directions. See figure 7a) and figure 7b).

10.3.2 Computation of the correction for width (method 1)

Ideally the correction for error in the computed width would be applied to that particular increment in the cross-section where the error occurred.

However in practice only the overall width is directly measured and thus is available for comparison with the computed quantities. Therefore, if the sum of the computed incremental widths does not equal the measured width of the cross-section, correction should be made by adjusting each increment proportionately.

The moving-boat method uses the relationship between the measured and computed widths of the cross-section to determine a width/area adjustment factor. To obtain this factor, the measured width of the cross-section is divided by its computed width, that is

$$k_B = \frac{B_m}{B_c} \qquad \ldots (11)$$

where

k_B is the width-area adjustment factor;

B_m is the measured width of cross-section;

B_c is the computed width of cross-section.

The factor is then used to adjust both total area and total discharge of the measurement as if the width error had been evenly distributed on a percentage basis across each width increment of the cross-section.

See table 1, for an example of an application of a width-area adjustment factor.

10.4 Adjustment for mean velocity in the vertical

10.4.1 General

During a moving-boat discharge measurement, the current meter is set at a predetermined fixed depth of say 1 m below the water surface (see clause 7) thus this technique uses the subsurface method of measuring velocity. Measurement is computed by using constant-depth subsurface velocity observations without adjustment coefficients as though each were a mean in the vertical. In using this method, each measured velocity should ideally be multiplied by a coefficient to adjust it to the mean velocity in its vertical. However, it is assumed that in the larger streams where the moving-boat technique would be applicable, these coefficients would be fairly uniform across a section, thus permitting the use of an average cross-section coefficient to be applied to the total discharge. Information obtained from several vertical-velocity curves, well distributed across the measuring site, is required to determine a representative coefficient for the total cross-section.

10.4.2 Determination of vertical velocity coefficient

Vertical-velocity curves are constructed by plotting observed velocities against depth. The vertical-velocity curve method calls for a series of velocity observations (by conventional methods) at points well distributed between the water surface and the stream bed. Normally these points are chosen at 0,1 depth increments between 0,1 and 0,9 of the depth. Observations should also be made at least 0,15 m from the water surface and 0,15 m from the stream bed.

Once the velocity curve has been constructed, the mean velocity for the vertical can be obtained by measuring the area between the curve and the ordinate axis with a planimeter, or by other means, and then dividing this area by the length of the ordinate axis (see ISO 748).

To obtain a velocity adjustment coefficient at any vertical i in the cross-section, the mean velocity in the vertical is divided by the velocity at the moving-boat sampling depth; that is,

$$k_v = \frac{\overline{v}}{v} \qquad \ldots (12)$$

where

k_v is the velocity adjustment coefficient;

$\overline{v}$ is the mean velocity in the vertical;

v is the velocity at the moving-boat sampling depth.

In order to arrive at a representative average coefficient, there should be at least several strategically placed verticals, representing a major portion of the flow, where coefficients are determined. The average coefficient is the weighted average value with weights in proportion to the discharge in the segments. Once an average coefficient has been determined, it should not be necessary to redetermine it each time when making future discharge measurements at the same site. However, it is necessary to test its validity at several stages, and, in estuaries, at widely different parts of the tidal cycle.

10.5 Application of the velocity adjustment coefficient

The velocity adjustment is made immediately after the width-area adjustment has been applied. For this adjustment, the total discharge, as determined from the subsurface velocity readings, is multiplied by the appropriate velocity-correction factor for the cross-section. The product is the measured value of discharge (see tables 1 and 2).

NOTE — Examination of many of the larger rivers around the world indicates coefficients that lie in the range of 0,85 to 0,92 for adjusting the subsurface velocity to the mean. A fairly comprehensive study covering 100 stream sites in the United States (depths varied from 3 m and over) indicate an average coefficient of approximately 0,90 to adjust the velocity obtained at 1,2 m below the surface to the mean velocity.

11 Accuracy of flow measurement

A general outline of the method of estimating the uncertainty of a measurement of flow is given below.

11.1 Sources of error

Due to the very nature of physical measurements, it is impossible to effect the measurement of a physical quantity with absolute certainty.

In addition to the uncertainty due to human error and instrument malfunction (spurious errors) there are three types of error which must be considered viz : random errors, constant systematic errors and variable systematic errors.[1]

The sources of error may be identified by considering a generalized form of the working equation (8)

$$Q = \sum_{i=1}^{m} b_i d_i \overline{v}_i$$

The overall uncertainty in the discharge is then composed of

a) uncertainties in width;

b) uncertainties in depth, both of individual soundings and readings of water level (see ISO 748 sub-clause 6.2.3);

c) uncertainties in determination of the subsurface velocity. These will depend on the accuracy of the apparatus and on the irregularity of the velocity distribution in time and space;

d) uncertainties in the use of the moving-boat method particularly those concerned with the number of segments, the determination of the velocity perpendicular to the cross-section and the velocity correction factor.

11.2 Determination of individual components of error

11.2.1 Uncertainty in width, X_{b_i}

If method 1 is applied, then according to equation (5)

$$\Delta l_b = \cos \alpha \int v_v \, dt$$

The uncertainty in the measurement of width depends on the random and systematic errors in the measurement of the time, the velocity and the angle, which are the basic variables from which the width is derived. The velocity is also a dependent variable, dependent on the measurement of pulses and time. When considering the measurement of time associated with the measurement of velocity, the instrumental errors are in most cases much less than all others and the error in this independent variable can be deleted.

The percentage uncertainty in the measurement of width, X_b, is found from :

$$X_b = \left[X_v^2 + (- \alpha \tan \alpha)^2 X_\alpha^2 + X_t^2 \right]^{1/2}$$

where α is in radians.

In the above equation, the sensitivity coefficients of the components v_v and t are 1. The sensitivity coefficient of the angle is $\alpha \tan \alpha$ which is approximately equal to 1 when $\alpha \approx 50°$ (0,87 rad).

When method 2 is applied, the uncertainty in the measurement of width is mainly an instrumental error depending on the instrument employed and the range of width. For optical instruments see ISO 748, annex E. For electronic instruments the uncertainty consists mainly of a constant part and a variable part dependent on the measured width as specified by the manufacturer.

Most of the possible errors are of a random nature and, with precautions, will introduce no bias into the measurement results; a few are systematic in nature and special care is needed to keep these to a minimum.

Error sources and recommended precautions are as follows :

a) Improper calibration of the current meter will result in a variable systematic error in measurements of width.

b) Readability of the angle is within ± 1°. The angle reader must exercise care to obtain accuracy within the readability of the angle and to avoid introducing operator bias.

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[1] For definitions and relevant formulae see ISO 5168.

c) Obliqueness of streamflow to the measuring section will cause an error in width measurements. Careful selection of the measuring site to avoid oblique flow is recommended. To compensate for the effects of oblique flow and large deviations of the boat from the selected path it is recommended that an equal number of runs be made in both directions along the cross-section. This is particularly desirable in cross-sections which are not symmetrical and where the bed profile is irregular.

d) A total width-correction adjustment should be applied (see 10.3.2) to minimise systematic errors.

11.2.2 Uncertainties in depth, X_{d_i}

The operating principle of the echo-sounder is based on the measurement of time between the transmission and reception of soundwaves (and the velocity of sound in water). Temperature and density deviations cause an improper calibration of the echo-sounder that will result in a systematic error in depth measurements. On-site calibration can be achieved by suspending a metal plate a known distance below the transducer.

Care should be exercised in reading the echo-sounder chart so that no systematic reading error is introduced. It should be noted that reading of the chart can also introduce a random error because of the parallax effect.

Rolling and pitching of the boat (and therefore of the sounder transducer) due to choppiness of water introduces a random error in depth measurement. This error can be reduced by selection of a boat which will be more stable in rough water conditions.

A further random uncertainty introduced by the irregularity of the bed profile itself, as the rugosity determines the reflection of the sound.

11.2.3 Uncertainties in determination of the subsurface velocity, X_{v_v}

The velocity at any point in the cross-section is continuously and randomly fluctuating with time. Therefore several runs should be made to minimise the influence of a limited measuring time. The magnitude of the pulsation error is also dependent upon the relative position in the "vertical"; the relative and absolute pulsation error is less in the upper part of the velocity distribution vertical. To obtain the smallest pulsation error the current meter should sense the velocity in the subsurface layer as previously stated.

11.2.4 Random and systematic uncertainties due to the current meter, X_c

When current meters are calibrated several times under the same conditions they show small random fluctuations for the same points on the rating curve. The same effect occurs in reverse when a current meter measures a velocity. This causes a random instrumental error in the determination of the flow velocity. The original random error in the determination of the rating curve, however, becomes a variable systematic error each time the same point is used for the determination of the flow velocity and for the discharge. This variable systematic error is randomised through the use of the rating curve which consists of more points at which the current meter is calibrated and the application of the rating curve being spread over different velocities.

Improper calibration or use of the current meter will result in a constant systematic error in velocity measurements.

A meter should therefore be recalibrated whenever its rating is in doubt.

Any deviations of the current meter's position from a plane parallel to the water surface will result in a velocity reading which is below the correct value. Using method 1, care should be taken to mount the vane assembly so that it will be perpendicular to the water surface during the period of measurement.

If the velocity is measured with a rate indicator, care should be exercised to avoid errors due to parallax or other reader bias.

11.2.5 Uncertainties in flow velocity, X_f (method 1)

From the equation (1)

$$v = v_v \sin \alpha$$

it can be seen that uncertainties in flow velocity, i.e. the velocity perpendicular to the cross-section, are dependent on the variables of total velocity v_v and the angle α. As stated in 11.2.6, the uncertainty in the measurement of time and pulses, which are the basic quantities to determine the velocity v_v, may be insignificant, and are neglected

From equation (13), it follows that the percentage random uncertainty in flow velocity, X_f can be computed from

$$X_f = \left[X_{v_v}^2 + (\alpha \cot \alpha)^2 \, X_\alpha^2 \right]^{1/2} \qquad \ldots (14)$$

When method 1 is applied, the following uncertainties may be used :

a) Readability of the angle should be within ± 1°. (The angle reader must exercise care to obtain accuracy within the readability of the angle and to avoid introducing operator bias.)

b) The readability of the rate indicator should be within ± 5 pulses per second.

11.2.6 Uncertainties in flow velocity, X_f (method 2)

From equation (2)

$$v = \sqrt{v_v^2 - v_b^2}$$

it can be seen that uncertainties in flow velocity determined according to method 2 originate from uncertainties in the total velocity v_v and the measured velocity of the boat v_b. The dimensionless sensitivity coefficients for v_v and v_b are

$$\frac{v_v^2}{v_v^2 - v_b^2}$$

and

$$\frac{-\, v_b^2}{v_v^2 - v_b^2}$$

respectively, (see ISO 5168).

Thus the percentage uncertainty in flow velocity can be computed from :

$$X_f = \left[\left(\frac{v_v^2}{v_v^2 - v_b^2} \right)^2 X_{v_v}^2 + \left(\frac{-\, v_b^2}{v_v^2 - v_b^2} \right)^2 X_{v_b}^2 \right]^{1/2} \quad \ldots (15)$$

The basic quantities to determine v_v are pulses from the current meter and the measured time. Depending on the apparatus used the errors in these basic variables may be insignificant.

The velocity of the boat v_b is determined from a distance measurement and a measurement of time needed to traverse the distance between observation points given by

$$b_i = l_i - l_{(i-1)}$$

Since $v_b = \frac{b}{t}$ the uncertainty in v_b consists of uncertainties in the variables b and t.

The percentage uncertainties in the measured v_b is therefore

$$X_{v_b} = (X_b^2 + X_t^2)^{1/2} \quad \ldots (16)$$

and the percentage uncertainty in the flow velocity becomes

$$X_f = \left[\left(\frac{v_v^2}{v_v^2 - v_b^2} \right)^2 X_{v_v}^2 + \left(\frac{-\, v_b^2}{v_v^2 - v_b^2} \right)^2 (X_t^2 + X_b^2) \right]^{1/2} \quad \ldots (17)$$

11.2.7 Total random uncertainty in flow velocity, X_{v_i}

Method 1

According to equation (14) and the prior discussion on uncertainties in the velocity measurement, the total percentage random uncertainty in flow velocity can be computed from :

$$X_{\bar{v}} = \left[X_{v_v}^2 + (\alpha \cot \alpha)^2 X_\alpha^2 + X_c^2 \right]^{1/2} \quad \ldots (18)$$

where

α is in radians, and

X_c is the random uncertainty in the current meter rating.

Method 2

The above treatment holds for the total random uncertainty in flow velocity measured by applying method 2. Thus the total uncertainty in flow velocity is constituted as follows :

$$X_{v_i} = \left[\left(\frac{v_v^2}{v_v^2 - v_b^2} \right)^2 (X_{v_v}^2 + X_c^2) + \left(\frac{-\, v_v^2}{v_v^2 - v_b^2} \right)^2 (X_b^2 + X_t^2) \right]^{1/2} \quad \ldots (19)$$

11.2.8 Uncertainties due to the use of the moving-boat method

These uncertainties are those particularly concerned with the number of segments and the relationship of the mean velocity in the vertical to the subsurface velocity.

Although there is continuous depth-sounding, only a limited number of depths are used to determine the area of the segment.

According to the mid-section method, the depths between verticals are linearly interpolated. This causes a random uncertainty X_{d_m} which decreases with an increase in the number of segments.

The horizontal velocity profile in the cross-section is a time integrated continuous velocity profile, and random uncertainties are therefore only due to velocity fluctuations as discussed in section 11.2.3.

As discussed in 10.4.2 a vertical velocity coefficient is required to adjust the measured total discharge. Deviations from the correct value for this vertical velocity coefficient determined for a certain stage lead to a variable systematic error which for a number of discharge measurements at the same stage can be randomized.

11.3 Overall uncertainty in measurement of discharge

The total uncertainty in the measurement of discharge is the resultant of a number of contributing uncertainties which may themselves be composite uncertainties (for example the uncertainty in the determination of width or the flow velocity), and will therefore tend to be normally distributed.

11.3.1 Overall random uncertainty, X'_Q

If X'_{b_i}, X'_{d_i} and $X'_{\bar{v}_i}$ are the percentage random uncertainties in b_i, d_i and $\bar{v}_i$ for each of the m segments, and X'_Q is the percentage random uncertainty in the discharge Q then

$$X'_Q = \pm \sqrt{ X'^2_{d_m} + \frac{\sum_1^m (b_i\, d_i\, \bar{v}_i)^2 (X'^2_{b_i} + X'^2_{d_i} + X'^2_{\bar{v}_i})}{\Sigma (b_i\, d_i\, \bar{v}_i)^2} } \quad \ldots (20)$$

Where X_{d_m} is as defined in clause 11.2.8.

Equation (20) can be simplified, if it is assumed that average values of X'_{b_i}, X'_{d_i} *and* X'_{v_i} are taken for all verticals and the discharge through the segments are nearly equal. With these assumptions equation (20) becomes

$$X'_Q = \pm \sqrt{X'^2_{d_m} + \frac{1}{m}\left(X'^2_b + X'^2_d + X'^2_{\bar{v}}\right)} \quad \ldots (21)$$

These calculations are based on estimated uncertainties related to one run in the cross-section. If it is accepted that the results of separate runs are independent then the uncertainty decreases according to the equation

$$X'_{Q_r} = \pm \frac{X'_Q}{\sqrt{r}}$$

where r is the number of runs.

For instance the uncertainty for six runs is nearly 2,5 times less than for one run.

11.3.2 Overall systematic uncertainty, X''_Q

Systematic uncertainties (constant as well as variable) which behave as random uncertainties should be estimated separately and may be combined as follows :

$$X''_Q = \pm \sqrt{X''^2_b + X''^2_d + X''^2_{\bar{v}}} \quad \ldots (22)$$

where X''_b, X''_d and $X''_{\bar{v}}$ are the percentage systematic uncertainties in b, d, and $\bar{v}$.

11.4 Presentation of uncertainty due to random and systematic uncertainties

There is no universally accepted method of combining random and systematic uncertainties and the presentation of the two components separately ensures that there can be no doubt as to the nature of the uncertainties involved.

Despite the fact that it is preferable to list systematic and random uncertainties separately it is appreciated that this can be confusing to readers of any report, and so it is permitted to combine them using the root-sum-square method, having first calculated the overall random and systematic uncertainties separately. When this is done, no confidence limits can be attached to the overall uncertainty, but the confidence limits of the random component should be given.

The overall uncertainty of the discharge will then be

$$X_{Q_m} = \pm \sqrt{X'^2_{Q_r} + X''^2_Q} \quad \ldots (23)$$

and can be reported in one of the following forms :

a) Discharge = Q

$(X'_Q)_{95} = \pm \ldots \%$

$X''_Q = \pm \ldots \%$

b) Discharge $Q \pm X_{Q_m} \ldots \%$

$(X'_Q)_{95} = \pm \ldots \%$

NOTE — In the above $(X'_Q)_{95}$ refers to the percentage random uncertainty at the 95 % confidence level.