International Standard 4369

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

Mesure de débit des liquides dans les canaux découverts — Méthode du canot mobile

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council.

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It has been approved by the member bodies of the following countries :

Australia	Germany, F.R.	Switzerland
Canada	India	Turkey
Czechoslovakia	Italy	United Kingdom
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Finland	Romania	USSR
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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.

1) At present at the stage of draft.

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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.

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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

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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

$$Q_\mathrm{m} = \sum_{i=1}^{i=m} b_i d_i \bar{v}_i \qquad \ldots (8)$$

where

Q_m is the calculated discharge;

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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

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

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

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

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.

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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,

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

where

k_v is the velocity adjustment coefficient;

$\bar{v}$ 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.

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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 :

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

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.

1) For definitions and relevant formulae see ISO 5168.

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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

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

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

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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 :

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

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

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

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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 :

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

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 $X'_{\bar{v}_i}$ are taken for all verticals and the discharge through the segments are nearly equal. With these assumptions equation (20) becomes

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

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.

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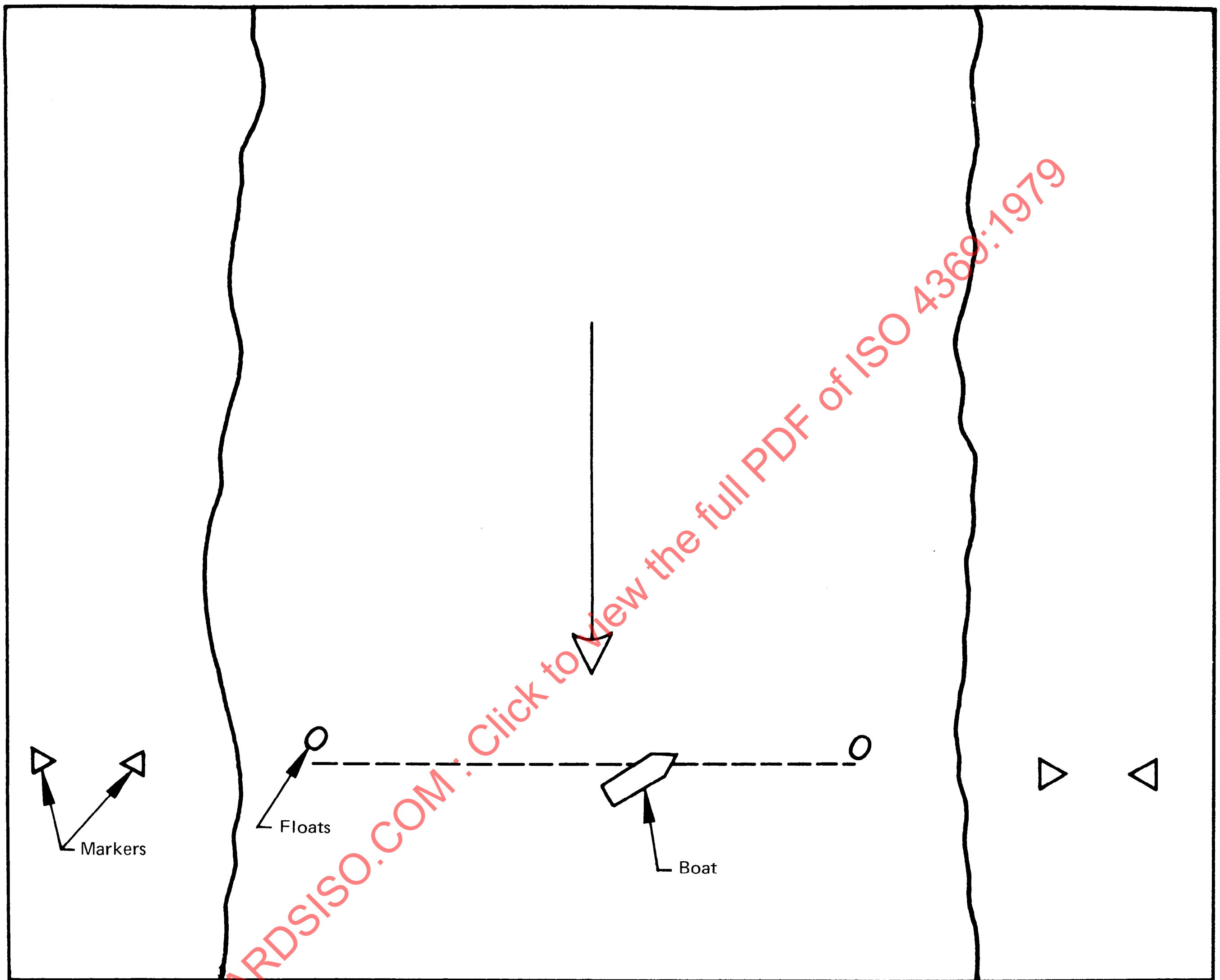

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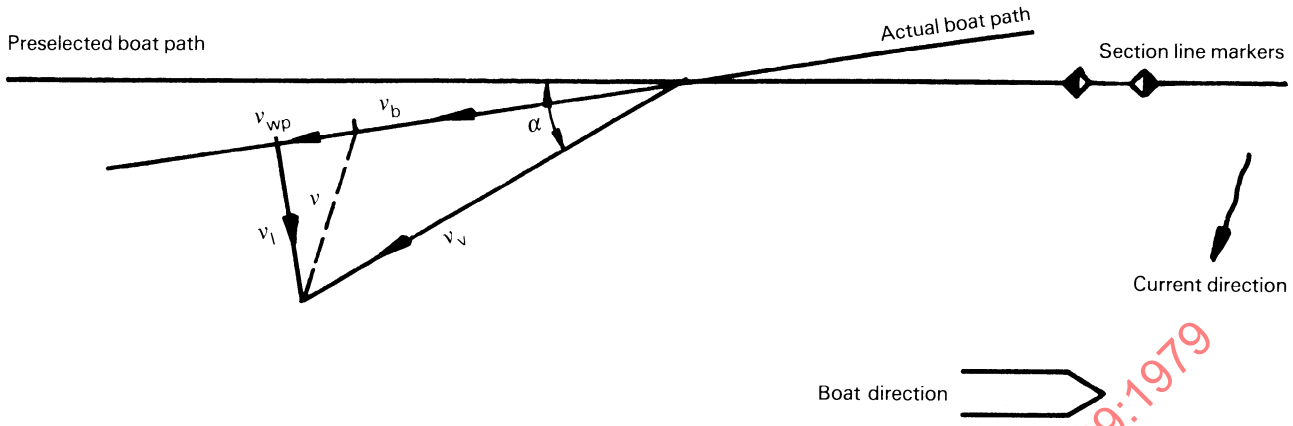
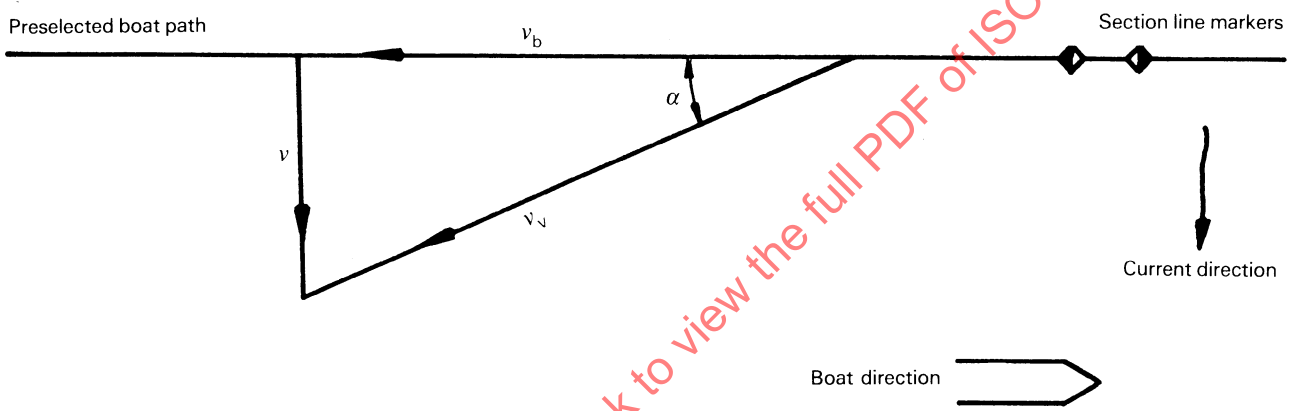
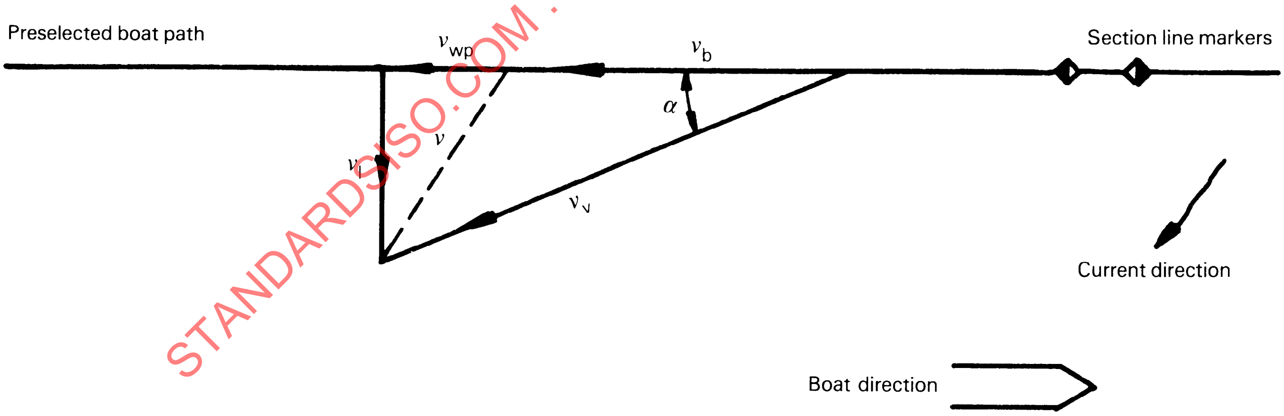
Figure 1 — Sketch of stream with markers



Case 1 — Boat not precisely on course and current at a skew angle to the preselected boat path



Case 2 — Boat on course and current perpendicular to it



Case 3 — Boat assumed on preselected path and current oblique

α angle between preselected boat path and v_v

v_v velocity of water as indicated by the current meter (called "total velocity" in this standard)

v velocity of water with respect to stream bed

v_l velocity of water perpendicular to boat path

v_b velocity of water with respect to boat as a result of boat movement only. This is opposite in sign to velocity of boat in respect to stream bed

v_{wp} velocity of water along the boat path as a result of stream flow only

Figure 2 — General diagrams of velocity vectors

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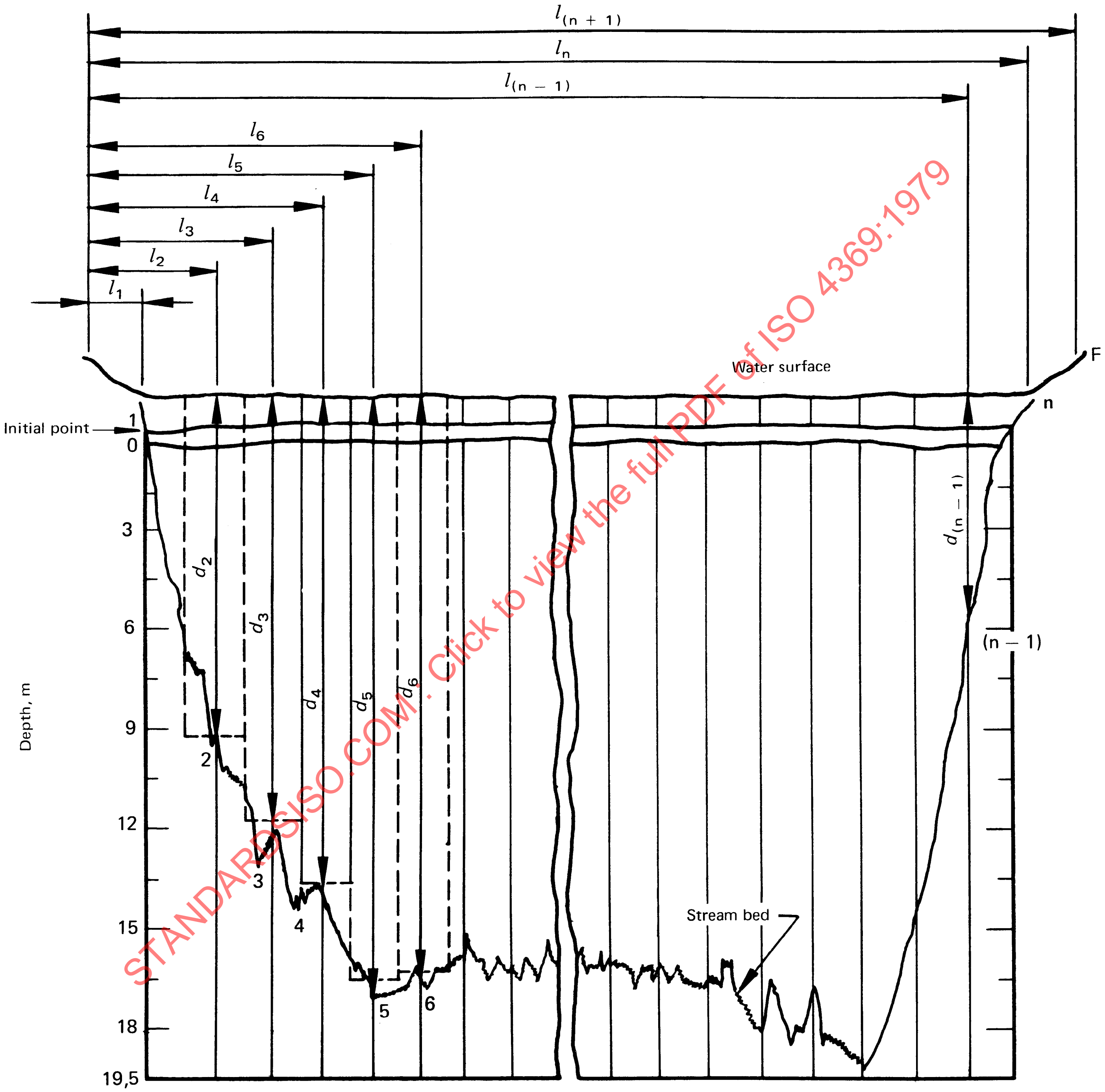

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Figure 3 — Definition sketch of midsection method of computation superimposed over a facsimile of a echo-sounder chart

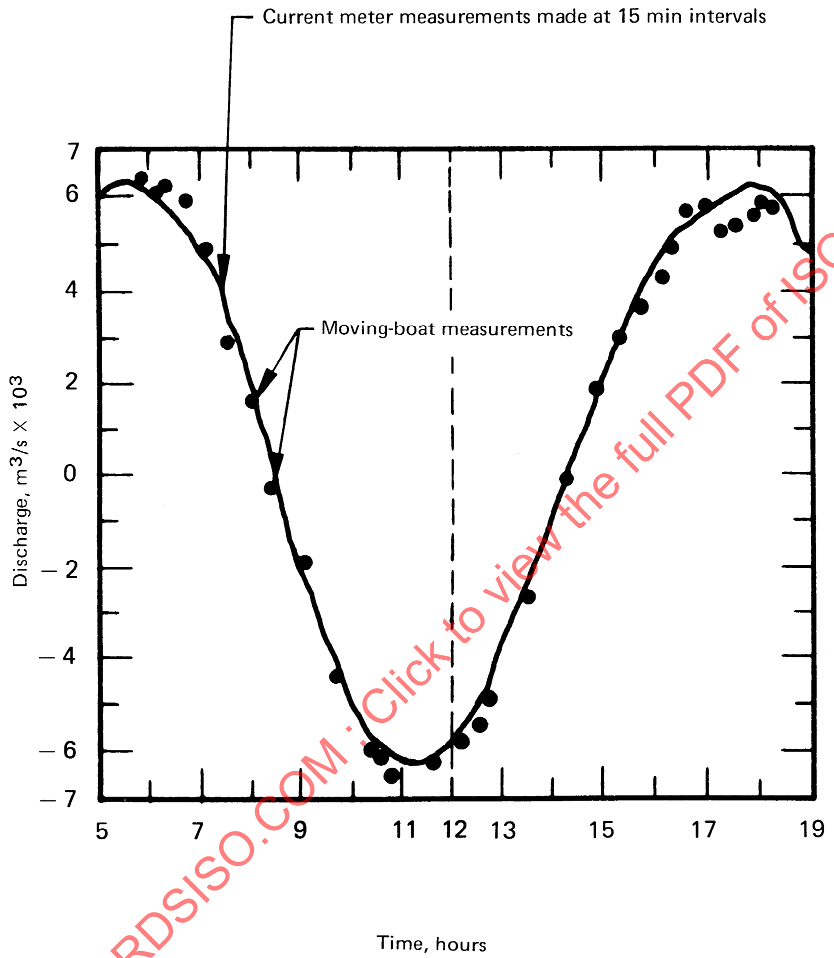

Figure 4 — Discharge hydrograph prepared from current meter measurements and showing moving boat check measurements; Hudson river at Poughkeepsie, N.Y., August 30, 1966

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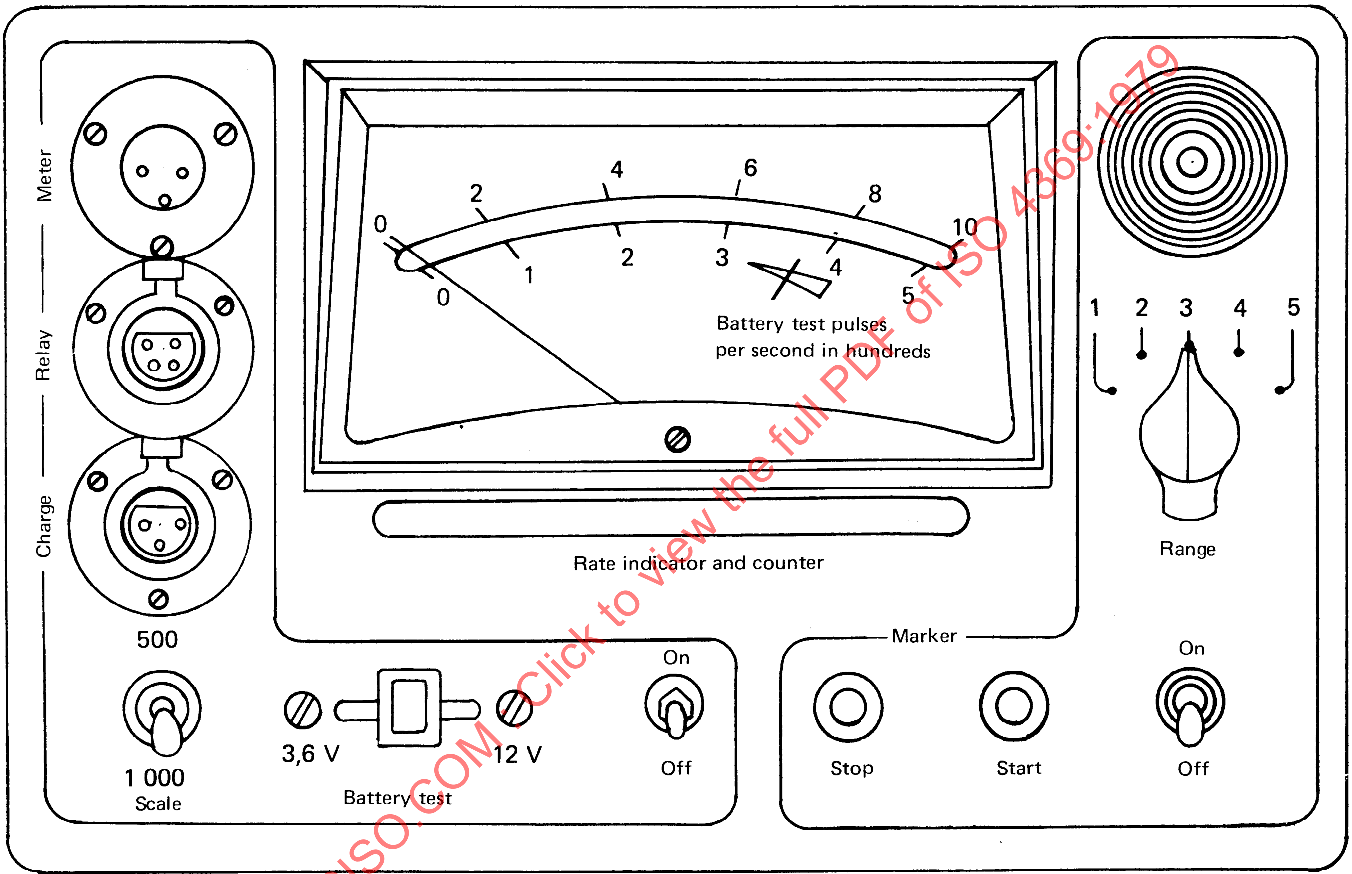

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Figure 5 — Typical control panel of rate indicator and counter — Method 1

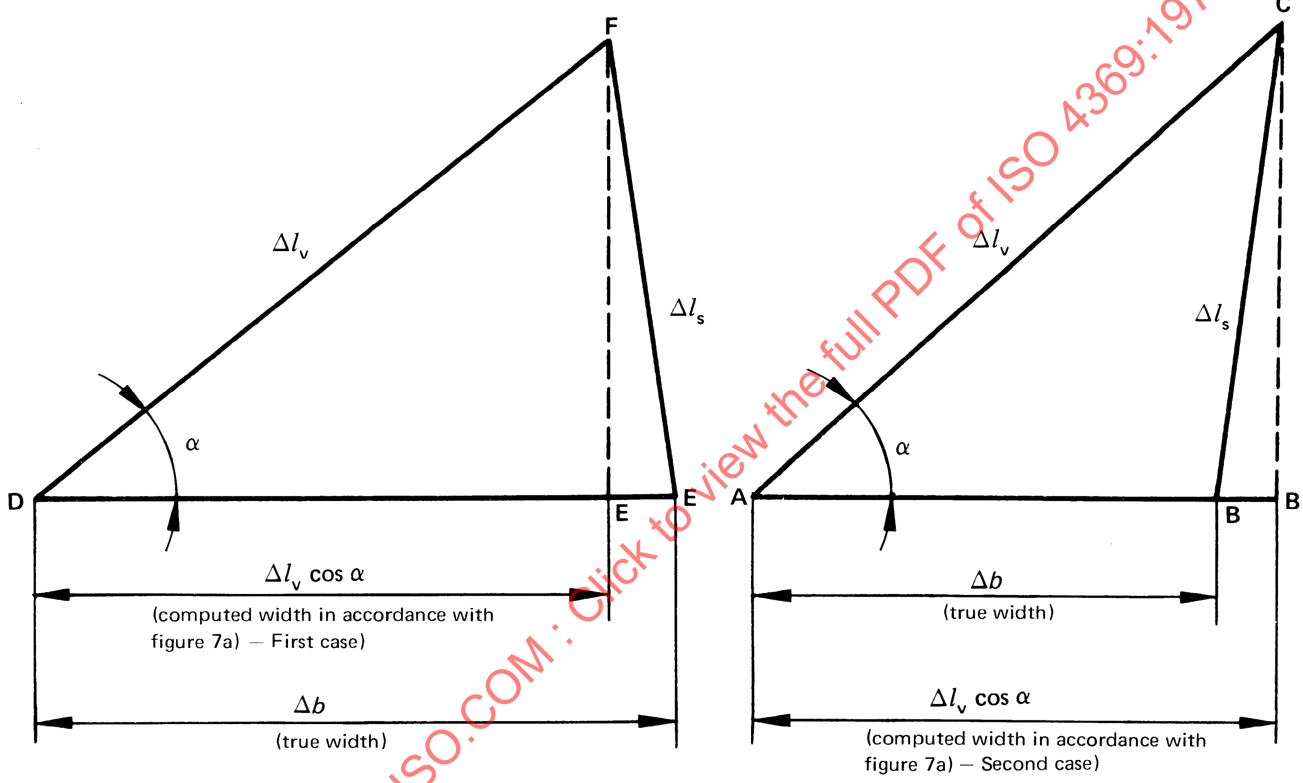

Figure 6 — Comparison of actual and computed values of incremental widths

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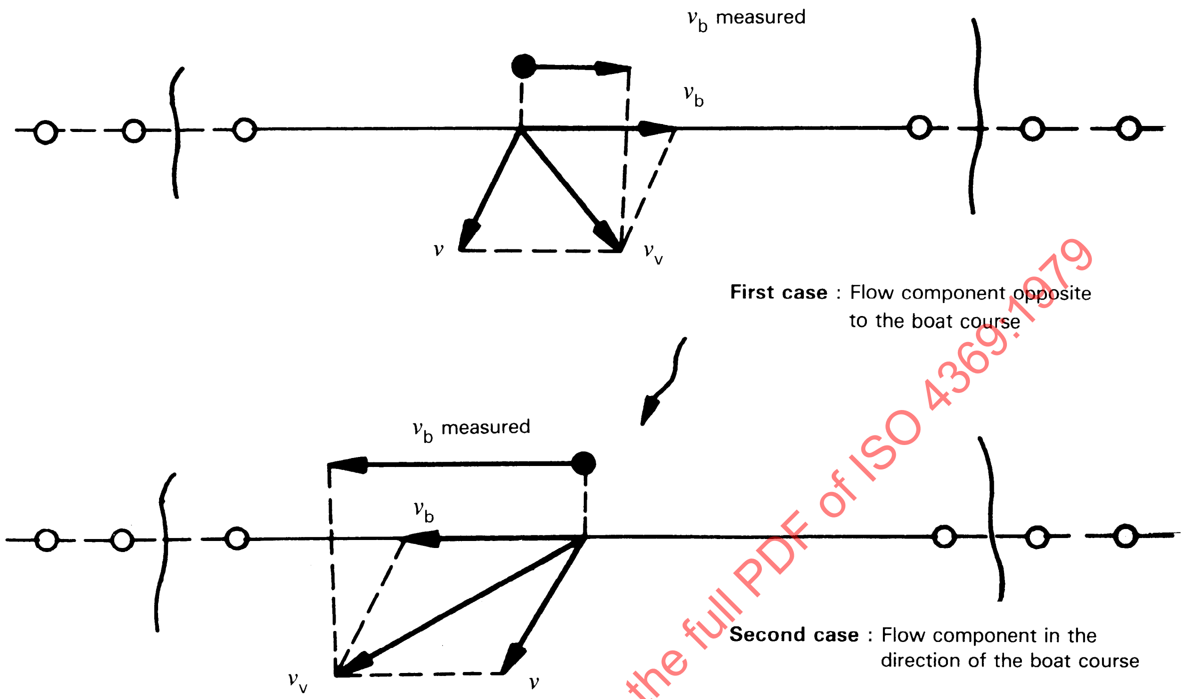
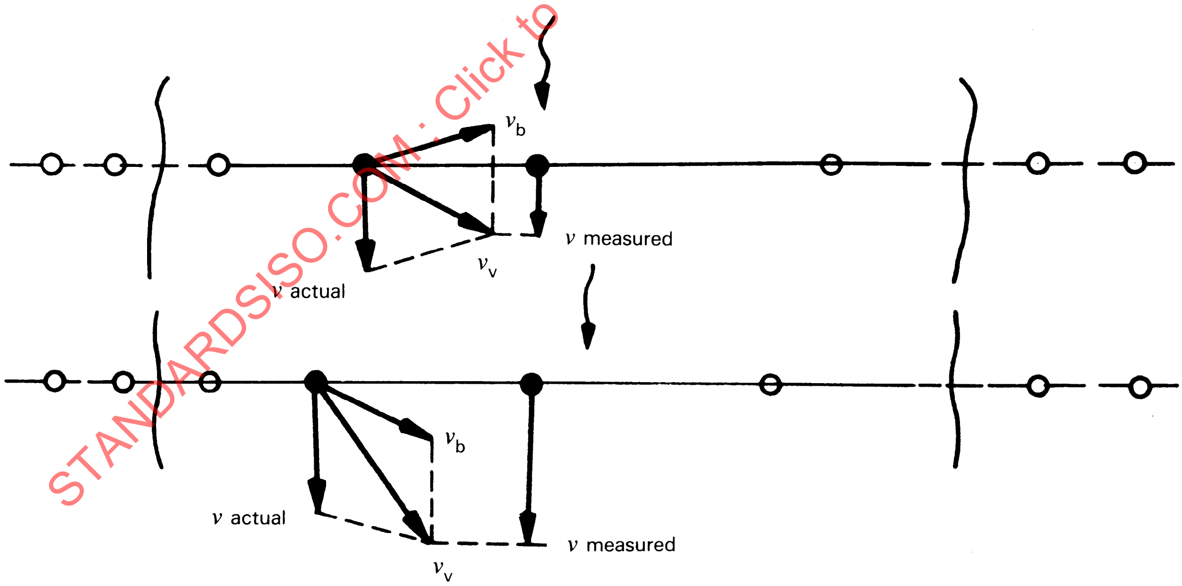


a) **Influence of oblique flow on boat velocity** v_b



b) **Influence of deviations between the boat path and the cross section on the measured stream velocity,** v

Figure 7 — Compensation for deviations from cross-section or in the direction of flow

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Annex A

Description of the instruments and the functions of the crew members

For the sake of accurate measurements it is of great importance that the experience already gained is taken into account; this holds especially for the instruments used and the functions of the crew members. The application of the moving-boat method in the field is a question of experience and routine.

Because of the importance of this, the instruments and the functions of the crew members are described in detail in this annex.

As in the main part of this International Standard, the two methods are dealt with separately. However, since method 2 is in fact a variant of method 1, the significant differences of the first method are stated in a separate sub-clause.

A.1 Equipment

A.1.1 General

Method 1

Specialised instrumentation consisting of an echo sounder, a vane with indicator, a special current meter with its associated electronic equipment and an easily manœuvrable boat with some modifications provide the capability needed for a moving-boat measurement.

A.1.2 Vane and angle indicator

A vane with an indicating mechanism is mounted on the bow of the boat, with the vane centred approximately 1 m below the water surface (see figure 8). This assembly consists of a vertical stainless-steel shaft with a pointer connected to its upper end and a thin vertical aluminium fin, 0,3 m high and 0,45 m long, attached to its lower end. The shaft is housed in an aluminium bearing tube and is mounted with ball bearings at the upper end and a teflon bearing (no lubrication is needed) in the lower end of the tube so that the assembly (vane, shaft, pointer) is free to rotate as a unit. The vertical vane aligns itself in a direction parallel to the movement of the water past it. The pointer is attached to the shaft so that it will be in line with the vane and pointing directly into the flow past the vane. The angle between the direction of the vane and the true course of the boat (the line of the cross-section) is indicated on a dial by the pointer. The circular dial, calibrated in degrees on either side of an index point, swivels freely about the upper end of the vertical shaft, just below the pointer. A sighting device attached to the dial provides a means of aligning the index point on the dial with the true course. In positive streamflow, the pointer above the dial will always point to the upstream side of the true course. Because the upstream side may be to the left or right side, depending on which direction the boat is travelling, and because of possible negative velocities, the dial is calibrated in degrees (from 0 to 90) on both sides of its index point.

A.1.3 Current meter

The current meter preferred is a component propeller-type with a special body made for mounting on the leading edge of the vane (see figure 8). The component propeller is less susceptible than are other types of meters to vertical components of velocity and was chosen to minimize errors created by the pitching and/or vertical motion of the boat.

A 24-toothed gear passing in the proximity of a magnetic field is used to generate 24 pulses per revolution of the propeller. The large number of pulses for each revolution facilitates the conversion of the pulse rate to an analogue or digital readout. An electronic pickup assembly registers these pulses and feeds them into a frequency-to-voltage converter, they are then displayed as a reading on an electrical meter.

A.1.4 Rate indicator and counter

One of the principal functions of the rate indicator and counter is as a frequency-to-voltage converter, and to display the number of pulses (see figure 5). These pulses are received via the current meter cable which is plugged into the marked receptacle provided in the front panel of the unit. The current meter generating the pulses is calibrated so that the reading on the electrical meter in pulses per second can be converted to a particular velocity (in m/s) through the use of a rating table (see tables 3, 4 and 5). The value read from the electrical meter at any particular instant represents an instantaneous readout of velocity.

In addition to serving as a pulse-rate indicator from which velocity determinations can be made, this unit has also been designed to provide a method of automatically selecting measurement points in a section at regular intervals of distance travelled. This design makes use of the fact that each revolution of the meter propeller generates 24 evenly-spaced pulses, and that from the calibration of the meter it can be determined that one pulse is equal to some fraction of a metre of travel through the water or water past the meter. By using a set of frequency-dividing modules, provision is made for these pulses to be electronically counted to a preset number at which time an audible signal is generated and the sounder chart is automatically marked. The counter then automatically resets itself and the process is repeated. The purpose of the audible signal is to let the boat crew know when a sampling location is reached. At this point they will take an angle reading from the pointer and a readout from the electrical meter. The markings on the sounder chart are automatically triggered by an electrical impulse transmitted to the depth-sounder unit by a relay in the meter electronics. The relay cable from the counter to the sounder should be plugged into the appropriately marked receptacle on the front panel of both units. The markings on the sounder chart locate observation points in the cross-section and thus show where depth readings should be taken.

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Preset intervals which are available on each unit are as follows :

Range selection	Pulse counts	Distance in metres (approximate)
1	1,024	6
2	2,048	12
3	4,096	24
4	8,192	48
5	16,384	96

The distances listed above are typical; exact ones depend upon the calibration of the particular current meter used. If possible, the pulse-selector switch should be set for a distance that will divide the measured width between the two floats into from 30 to 40 increments.

Analogue rate indicators and counters have been developed which make provision for the first pulse count after the start to be a half count. This facility helps minimize errors during the start of the run when the boat could be accelerating and the observed angle changing more rapidly than usual.

A.1.5 Echo sounder

A portable echo sounder is used to provide a continuous strip-chart record of the depth of the stream; that is, a profile of the cross-section between the two floats. Its transducer releases bursts of ultrasonic energy at fixed intervals. The instrument measures the time required for these pulses of energy to travel to the stream bed, to be reflected, and to return to the transducer. With a known propagation velocity of sound in water, the sounder computes and records the depth. The sounder used in this application may be a commercially available model.

One minor modification to the echo sounder is the installation of a receptacle on its front panel into which is plugged the relay cable from the rate indicator and counter. The purpose of this relay connection is to transmit the electrical pulses from the counter unit which will automatically trigger the vertical-line markings on the sounder chart at each observation point.

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A.2 Functions of the crew members

A.2.1 General

Three crew members are necessary for making a moving-boat discharge measurement. They comprise a boat operator, an angle observer and a notekeeper. 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 phases of the technique. This can be done by making practice measurements at a site where the discharge is known and then comparing the moving-boat discharge with the rated discharge. If there is no suitable site available for this purpose, then the boat crew should make a series of moving-boat measurements at a single location and compare results for repeatability.

A.2.2 Boat operator

Before the measurement begins, the boat operator should become thoroughly familiar with the sampling site. In tidal streams the operator should be familiar with conditions during all phases of the tidal cycle. This will help avoid running the boat aground in shallow depths and damaging the submerged equipment. While manœuvring the boat, it is necessary to avoid sudden sharp turns that might damage the meter cable by causing it to be wrapped around the vane assembly.

The operator should select an approach path for the boat that will allow it to be properly manœuvred into position prior to passing the first float. The path should begin from a downstream position as close to the riverbank as depth considerations permit. From such a starting point, the boat can be accelerated to near its normal operating speed and the turn into the measuring section can be completed before the measurement begins. By attaining both the proper speed and alignment prior to reaching the float, the instrument reading will have time to stabilize before the initial sample is taken.

During a traverse, the boat operator's sole function is to pilot the boat. He maintains course by "crabbing" into the direction of flow sufficiently to remain on line throughout the run. As varying stream velocities are encountered in the cross-section, he should rely more upon steering adjustments to keep the proper alignment than upon acceleration or deceleration of the boat. Alignment is determined by sighting on the shore which is being approached. Much of the accuracy of the measurement depends on the skill of the boat operator in maintaining a true course.

A.2.3 Angle observer

A second operator aligns the dial of the vane indicator through its sighting device and, upon the audible signal from the pulse counter, reads the angle formed by the vane with respect to the true course. The operator reports the angle to the notekeeper who then records it. If the boat has strayed from the true path, the angle reader should sight parallel to the cross-section markers rather than at the markers themselves.

A.2.4 Notekeeper

The notekeeper has several functions to perform. Prior to the measurement it is the notekeeper's responsibility to see that all preparation of equipment as it pertains to the rate indicator and counter and the echo sounder is completed satisfactorily. This includes not only the assembly of equipment, but also the selection of appropriate instrument settings.

It is the notekeeper's responsibility to operate the controls provided on the equipment for starting and stopping the counter. It is important to the accuracy of the measurement that this unit promptly begins and ends its operation at the first and second floats, respectively.

A.3 General

Method 2

As described in the main part of this International Standard, the principle of method 2 is the same as for method 1 other than the angle measurement. Therefore, the instruments used show some differences and the function of the angle observer is replaced by the distance observer.

A.3.1 Distance meter

The distance meter can be an optical one, for example a normal range finder or an electronic one, for example a radiolog.

The most important facility is that it can be connected electrically or electronically with the echo sounder to mark the observation points on the strip chart.

A.3.2 Current meter and counter

The current meter is a propeller type which gives one pulse for one revolution. Otherwise the specification is as for method 1.

Counting the pulses can be done in three ways :

a) With a preset number of pulses. When this number is reached the observation point is marked on the sounder chart.

b) The width of the segments is equal, so the observation points are equidistant.

The counter with clock are switched from the range finder or radiolog.

Time and pulses are read off from the counter.

c) The time intervals for traversing the segments are taken as equal. In this system the clock of the pulse counter sends a signal to the relays of the counter, which is stored. The counting function is immediately switched by the relay to another counter, which is automatically reset at zero after say 5 s. The electronic clock also triggers the echo sounder which marks the strip chart and the distance display of the radiolog where the measured distance is displayed for some time.

As the measurement of time is one of basic importance, the counting apparatus requires an electronic clock and two displays which show alternately the counted pulses from the current meter (1 : 1).

If a preset number of pulses is used the counter should have thumb wheels to preset this number of pulses.

To be able to measure distance with an optical instrument, the counter should be provided with an audible signal so that the distance observer is given a warning to read the instrument.

A.3.3 Distance observer

If method 2 is applied the function of the second observer is to observe the distance. If the distance is measured optically (for example with the aid of a range finder) then the distance observer, upon an audible signal of the pulse counter, reads the distance to one of the markers on the bank. At the same time a mark is made on the strip chart of the echo sounder as the range finder is connected by electric cables to the echo sounder. The observer reports the distance to the notekeeper who records it.

If an electronic distance measurement is applied then the only difference to the optical one is that the distance observer reads the distance directly from an electronic counter. The marking of the strip chart is done by hand or, where equal distance intervals are used instead of an equal number of pulses from the current meter, it can be performed automatically.

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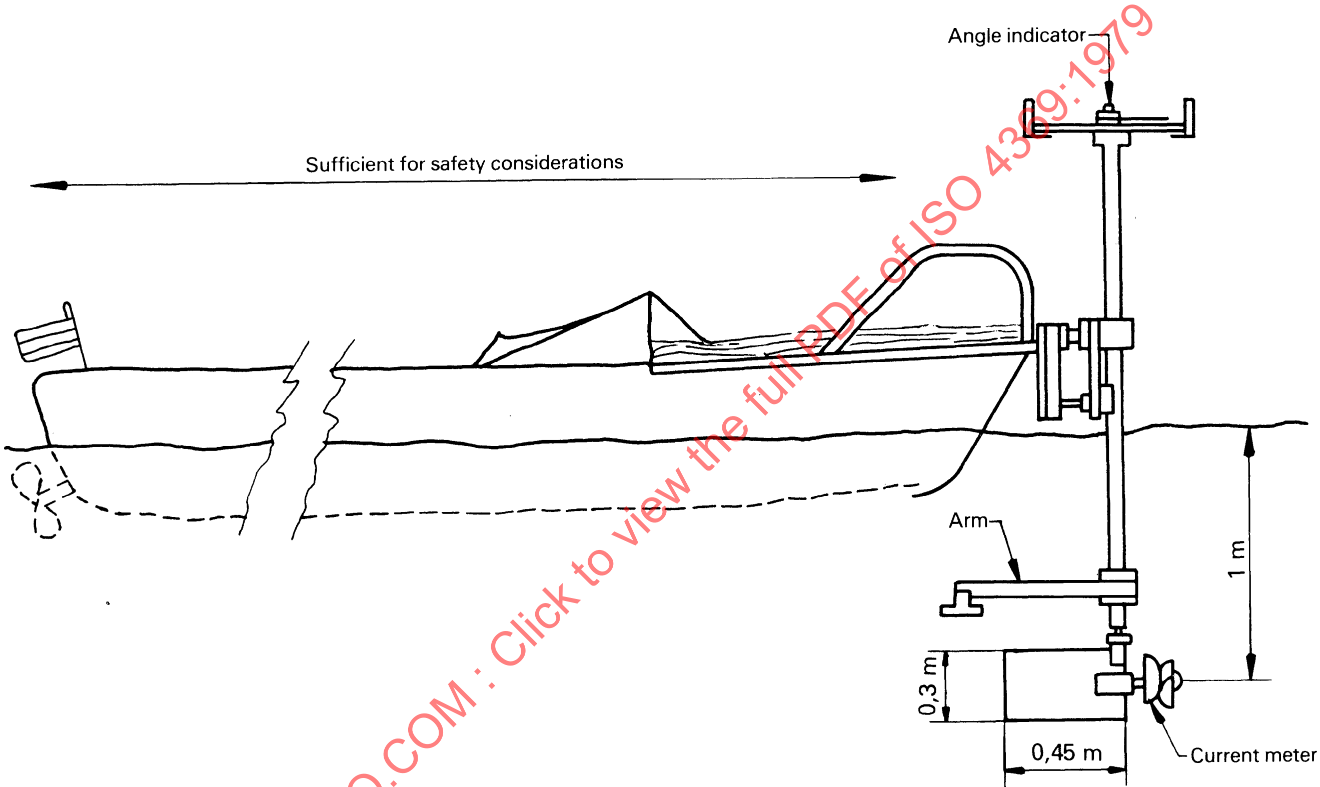

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Figure 8 — Sketch of boat showing equipment — Method 1

Annex B

A step-by-step outline of the computation procedure which refers to the examples of measurement notes for method 1 and method 2 shown in tables 1 and 2 respectively as a guide to the computer

B.1 Method 1 (see table 1)

B.1.1 The data in the first column are angle readings recorded by the notekeeper during the measurement. Because these readings begin and end at the float position (there are no edge-of-water readings), they represent the values observed at locations 2, 3, 4, . . . $(m - 1)$.

B.1.2 Each value in column 2 represents an incremental distance the boat has travelled along the cross-section path between two consecutive observation points. With α_i representating the angle reading at location i, then Δl_{b_i} is the incremental distance the boat has travelled along the true course, extending from the previous observation point, $i - 1$, to the location i where the reading was taken.

The values in this column can be read directly from table 4 by using the angle values recorded in column 1, and the range number as determined by the range selection on the counter unit. Two exceptions are the first and last values in the column, representing the distance to each float from its nearest edge of water.

B.1.3 Each value recorded in column 3 represents the distance from the initial point (marker) to the observation point where the data were collected (see 10.2).

B.1.4 Each of the segment widths in column 4 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 segment i equals

$$\frac{l_{(i+1)} - l_{(i-1)}}{2}$$

(see 10.2)

B.1.5 Each of the values in column 5 represents the stream depth at an observation point in the cross-section.

B.1.6 The data in column 6 are the pulses-per-second readings recorded by the notekeeper during the measurement.

B.1.7 The values recorded in column 7 represent the instantaneous velocity of the water past the vane at each observation point. They are read directly from the meter-rating table (table 3) using the pulses-per-second values of column 6.

B.1.8 The data in column 8 are the sine function values of the angle readings in column 1. These values may be obtained from table 5.

B.1.9 Each of the values in column 9 represents the stream velocity normal to the cross-section at that particular sampling point. To obtain these values, it is necessary to multiply each v_v value in column 7 by the corresponding sin α value in column 8.

B.1.10 The values in column 10 represent the individual segment cross-section areas for the measurement. They are obtained by multiplying the widths of column 4 by their corresponding depths in column 5. The incremental areas are then summed to provide the total unadjusted area for the measurement.

B.1.11 Each quantity in column 11 represents the unadjusted discharge through one of the segments of the discharge measurement. These values are summed to provide the total unadjusted discharge of the measurement.

B.1.12 Column 12 is used for recording any descriptive remarks pertaining to the measurement.

B.2 Method 2 (see table 2)

B.2.1 The first column gives the direct measured distance to the marker on the embankment.

B.2.2 Column 2 contains the width of each segment obtained by subtracting distances from column 1.

B.2.3 At each observation point marked on the echo sounder strip chart the depth is read off as shown in column 3.

B.2.4 The number of pulses obtained during a 10 second period when the segment was traversed is noted in column 4.

B.2.5 From a rating table or the rating curve the velocity is read off or computed using the number of pulses in column 4.

B.2.6 The velocity of the boat is determined from the width of the segment as presented in column 2 and the measuring time, is in this case 10 s.

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B.2.7 The flow velocity, v, is computed from equation (2)

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

B.2.8 The area of the segment (column 8) is obtained by multiplying the widths in column 2 by the corresponding depth in column 3.

B.2.9 The discharge through the segment is the product of column 7 and 8.

B.2.10 The total discharge is the sum of the partial discharges. The total discharge is adjusted by multiplying by the velocity correction coefficient.

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