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Measurement of flow in tidal channels

Mesure de débit dans les canaux à marée

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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.

International Standard ISO 2425 was drawn up by Technical Committee ISO/TC 113, *Measurement of liquid flow in open channels*, and circulated to the Member Bodies in September 1971.

It has been approved by the Member Bodies of the following countries :

Austria	Ireland	Spain
Belgium	Japan	Switzerland
France	Netherlands	United Kingdom
Germany	Romania	U.S.A.
India	South Africa, Rep. of	

No Member Body expressed disapproval of the document.

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Measurement of flow in tidal channels

0 INTRODUCTION

This International Standard provides information about the measurement of liquid flow in tidal channels, which poses problems additional to those encountered in uni-directional streams. Two different methods used generally for measuring tidal flow are covered by this International Standard :

a) direct measurement of flow by the measurement of velocities and cross-sectional areas, and

b) cubature methods.

For various reasons, direct measurements of velocity in tidal channels are more liable to large errors than are those made under conditions of uni-directional flow.

An important feature of this International Standard is clause 10, dealing with errors in tidal flow measurement, both in the direct measurements (10.1) and in methods of measurement by cubature (10.2).

Annexes are included to illustrate examples and applications of the two basic equations which are to be used with the cubature method.

1 SCOPE AND FIELD OF APPLICATION

This International Standard, which forms a supplement to ISO 748, specifies the methods of measurement of velocities in tidal channels to be applied in order to draw the total discharge curve and to compute the ebb and flood volumes. It also specifies the alternative method of cubature.

2 REFERENCES

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

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

3 TERMINOLOGY

For the purposes of this International Standard, in addition to the definitions given in ISO 772, the following definitions shall apply.

3.1 cubature : A numerical technique of computing discharges in a tidal channel at a cross-section from the rates of change in volume of water up to the tidal limit, with algebraic allowance for the fresh water discharges entering the channel.

3.2 density current : The phenomenon of gravity flow of a liquid relative to another liquid, or of relative flow within a liquid medium due to difference in density.

NOTE — The salt-water wedge is a specific case of density current when stratification occurs between identifiable flow masses (see 3.7).

3.3 ebb-tide : The occurrence of falling water surface of a tide.

3.4 ebb-current : The seaward movement of water along a tidal channel.

3.5 flood-tide : The occurrence of rising water surface of a tide.

3.6 flood-current : The landward movement of water along a tidal channel.

3.7 salt-water wedge : The wedge-like intrusion of a large mass of salt water flowing in from the sea under the fresh water in a tidal waterway, where mixing by turbulence is inappreciable.

3.8 estuary : A partially enclosed body of water in the lower reaches of a river which is freely connected with the sea and which may generally receive fresh water supplies from upland drainage areas.

3.9 tide : The periodic rise and fall of the water due principally to the gravitational attraction of the sun and moon.

3.10 tidal channel (tidal waterway) : The channel in which the flow is subject to tidal action.

NOTE — A tidal waterway consists of one or more tidal channels together with the shallows and the banks or sides by which the flow at high water is bounded.

3.11 tidal prism : The volume of water that flows into a tidal channel and out again during a complete tide, with the movement of the tide, excluding any upland discharges.

3.12 tide range : The difference in level between high water and low water of a tide. The range is specific to a particular tide if consecutive high and low water are used. Otherwise, the range can refer to extremes of high and low water over any specified period of time. (Tidal amplitude may be regarded as the difference between the water level at high or low water and mean sea level at a given point or the mean elevation of the tide.)

4 UNITS OF MEASUREMENT

The units of measurement used in this International Standard are seconds, and metres or feet.

5 PRINCIPLES OF THE METHOD OF MEASUREMENT

The alteration of the direction of flow in tidal channels creates problems of measurement additional to those associated with the measurement of the discharge of uni-directional streams.

The methods specified in ISO 748 cannot, therefore, be fully applied to tidal channels.

In tidal channels, the flow is generally measured by one of the following methods.

5.1 Velocity-area method

A gauging station is selected complying with the required conditions, and its width is measured by one of the usual methods of survey; the depth is measured in a certain number of verticals distributed in the section, the number chosen being adequate to determine the profile and the area of the section. The velocities are measured with a current-meter at different points on each of the verticals selected for the section. The number of verticals and the number of points on each vertical depend on the required precision and the availability of boats and meters. Necessary corrections have to be made to the velocities for the varying directions of flow, particularly in the presence of a salt-water wedge.

These velocity measurements are carried out at least for the full duration of a tide and the intervals between successive measurements on the same vertical are as short as possible. The measured velocities are then reduced to the same instant and the flow at this instant is calculated by multiplying the mean velocity by the cross-sectional area of the stream.

5.2 Moving-boat method

The moving-boat method employs a modification of the conventional current-meter measurements in the velocity-area method of determining discharge. The method requires no fixed installation and lends itself to the use of alternative sites if conditions make this desirable. Necessary corrections have to be made to the velocities for the varying directions of flow, particularly in the presence of a salt-water wedge.

5.3 Cubature method

Discharges are computed from the changes in the volume of water in the channel at short intervals of time. Water level and widths are simultaneously observed at suitable intervals of time at a number of stations along the channel up to the tidal limit. The areas of water surface corresponding to various water levels are determined from each reach. Changes in the volume of water during the specified time-intervals are computed. If the discharges of fresh water from the river at the head of the tidal channel and from other water tributaries are known, then starting at the head of the estuary, each successive reach can be considered in turn and the algebraic sum of the volume of seaward flow at the inland end of the reach, the volume of flow of tributaries into the reach and the decrease of the volume of water contained in the reach will give the volume of flow seaward during the specified time-interval at the cross-section at the seaward end of the reach. This volume divided by the time-interval gives the discharge at the cross-section.

6 MEASUREMENT DIFFICULTIES AND CHOICE OF METHOD

6.1 Particular difficulties encountered

Tidal action is the cause of a number of the possible difficulties listed below, but it must be stressed that sometimes, particularly in the upstream part of the tidal channel, this action will not cause a change in direction of flow but will manifest itself in a form of pulsating flow. In this case, although the flow is always in the same direction, the use of methods in ISO 748 will not be sufficient and this International Standard will apply.

The tidal difficulties are :

a) continuous change of water levels with or without changes in the direction of flow with time;

b) in a vertical at the same depth, continuous variation of the velocity with time and, at different depths, greater velocity gradients than in rivers with flow in the same direction;

c) changes in the distribution of velocities with time;

d) during the transition period from flood current to ebb current, or vice versa, there is a change of direction of current with an intermediate zero velocity;

e) the occurrence of high water and low water may not take place at the same time as the change in the direction of current;

f) the change in the direction of current does not take place at the same time throughout the width and depth of the waterway;

g) there may be stratification of flow by density currents (a salt-water wedge) with the upper strata flowing in one direction and the lower strata flowing in the reverse direction, the change of direction of current and the maximum velocity occurring at different times at different depths;

h) large and rapid variations of the width and capacity of the sections due to successive covering and uncovering of the banks by the tide;

j) presence of macroturbulence (for example, pulsations with a period of more than 30 s and an amplitude of up to 50 % of the mean velocity have been measured) and seiches.

6.2 Selection of the method of measurement

It should be noted that the velocity-area method requires a considerable number of observations at one cross-section, while the cubature method requires fewer observations and at more than one cross-section, these being of levels and areas only.

The choice of the method of measurement will be determined by the size and the shape of the channel, by the tidal amplitude and possibly by the presence or absence of a salt-water wedge.

6.2.1 As stated in 6.1, any direct measurement of velocity in a tidal channel is subject to greater errors than measurement of flow in rivers, where the current always flows in the same direction. Because of this, the usual corrections are not completely satisfactory. Due to the continuous variation of the flow, it would be necessary to measure velocities simultaneously and continuously and in a large number of verticals for an entire tidal cycle, and especially in the case of large rivers with wide estuaries considerable equipment is required. This method is especially difficult when

a) there is a large tide range;

b) there is a high density of traffic, which might interfere with the measurements;

c) the width of the waterway varies between wide limits during a single tide;

d) the mean direction of flow changes through a considerable angle during the ebb-tide or during the flood-tide.

Direct measurements of velocity might be desirable for particular reasons, for example, the study of density currents or the distribution of velocities in specific zones.

6.2.2 In all other cases, it is generally better to use one of the indirect methods of cubature that are comparatively easy and rapid, particularly due to the use of the modern electronic computer and calculator. It would, however, be difficult to use these, and the accuracy will decrease, in the following cases :

a) if the tide range is small;

b) if there are a large number of flat spill areas and a large variation of the tidal volume corresponds to only a small variation of the level of the water surface;

c) if the topography of the tidal estuary is not well defined due to the existence of large mud or silt flats, which are submerged during a part of the tidal cycle and which are subject to frequent alterations;

d) if the tidal channel is interlinked with the other tidal channels when there is generally a residual flow from one channel to another.

7 DIRECT MEASUREMENT OF TIDAL FLOW

7.1 Selection and demarcation of site

7.1.1 *Initial survey of site*

It is desirable that approximate measurements of widths, depths and velocities be made in a preliminary survey to decide on the suitability of a site conforming as far as possible with the conditions given in 7.1.2 and 7.1.3. It is only intended that these measurements should serve as a guide that both the longitudinal and transverse bed profiles and the velocity distribution are acceptable for the purpose of discharge measurement.

7.1.2 *Selection of site*

The accuracy of the determination of the discharge by the velocity area method is increased if :

a) the tidal cycle during which the measurement is carried out is periodical or almost periodical (small daily inequality);

b) the velocities at all points, particularly during the period of maximum flow, are at right angles to the measuring section;

c) the curves of the distribution of the velocities are regular in the vertical and horizontal planes on which they are measured;

d) the geometric dimensions of the cross-section of the open channel are clearly defined.

Hence, the most favourable conditions for accurate measurements are to be found where the cross-section is in a straight reach. On this basis, therefore, the site shall be selected such that, as far as possible, the requirements and points given in 7.1.3 are met.

7.1.3 The site selected shall comply, as far as possible, with the following requirements :

a) the open channel at the gauging site shall be straight and of uniform cross-section;

b) the depth of water in the selected reach shall be sufficient to provide for the effective immersion of the current-meters;

c) the view from the gauging site shall be clear and unobstructed by trees or other obstacles;

d) the bed of the reach shall not be subject to changes during the period of measurement;

e) all discharges shall be contained within a defined channel or channels, or within an unobstructed floodway having substantially stable boundaries, with well-defined geometrical dimensions;

f) the site shall be remote from any bend or natural or artificial obstruction if disturbance of the flow is likely to be caused thereby;

g) the gauging site shall be kept clear of aquatic growth during the period of measurement;

h) measurement with converging, and even more so with diverging, flow over an oblique measuring section shall be avoided as it is difficult to allow for the systematic errors that can arise;

j) the orientation of the reach shall be such that the direction of flow is as closely as possible normal to that of the prevailing wind;

k) sites at which eddies, backward flow or dead zones tend to develop shall be avoided.

Where these requirements cannot be met (for instance, when in alluvial rivers the river bed is changing during the period of measurement, or when, under high-water conditions the river is not confined to a single channel in embankments), a gauging site shall be chosen such that the bed change and/or overflow is a minimum. Flood-plains — if they cannot be avoided — must be of minimum width, as smooth as possible, without a distinct channel and clear of bushes and trees.

7.1.4 If, after the site has been selected, unacceptable changes occur in the channel conditions, another site shall be selected for the measurements.

7.1.5 The site, after selection, shall be provided with means for demarcation of the cross-section and for determination of the stage.

7.1.5.1 The position of the cross-section, normal to the mean direction of flow, shall be defined on the two banks by clearly visible and readily identifiable markers.

7.1.5.2 A gauge or a number of gauges shall be read throughout the measurement and the datum of these gauges shall be related by precise levelling to a standard system of levels.

The sites selected for these gauges shall comply, as far as possible, with the following requirements :

a) a gauge shall be read at the gauging site itself. Where there is a likelihood of a difference in the level of water surface between the two banks, an auxiliary gauge shall be installed on the opposite bank. This is particularly important in the case of very wide rivers. The mean of the measurements taken from the two gauges shall be used as the mean level of water surface;

NOTE — When the difference in level of water surface between two banks is very large, the lateral velocities induced may cause significant disturbance to velocity measurements. In such cases velocity corrections may not be accurate and should preferably be excluded.

b) in order to obtain information about meteorological influences on the tides during the measurement, gauges shall be read at the seaward end of the estuary, preferably at a location for which tidal predictions are available;

c) if there are cross-connecting creeks with other tidal inlets, or if the measurement is carried out in such a cross-connecting creek, gauges shall be read at the nearest junctions on either side of the gauging site;

d) an additional gauging site shall be fixed at a location above the tidal limit where the stage-discharge relationship is known, in order to determine the upland discharge.

7.2 Measurement of cross-sectional area

For this subject, clause 6 of ISO 748 applies without any alterations.

7.3 Measurement of velocity

7.3.1 *Measuring procedure*

In order to draw the total discharge curve and to compute the ebb and flood volumes, it is necessary to measure the velocity distribution in every vertical during at least one complete tide, that is, from one high/low water to the next high/low water. The time-intervals between the successive measurements in each vertical shall be short. The measurements shall be started and completed at least half an hour before and after the tide turns in order to determine accurately the time of zero velocity.

In localities where the diurnal inequality is large, observations shall continue for the entire tidal day, that is 26 h including half an hour before the tide turns and half an hour after the fifth turn of tide.

To enable an accurate tide curve to be drawn, the water level shall be read at intervals of not more than 10 min during the whole of the period of measurement.

The measuring procedure that shall be followed depends largely on the existing conditions.

a) When enough boats and measuring equipment are available, a measuring boat shall be stationed in every vertical, and in all verticals the velocity distributions shall be measured simultaneously during a complete tide.

b) When a limited number of boats are available, suitable verticals shall be located and marked with anchored buoys. At least one boat shall remain stationed at one reference vertical taking a series of velocity observations during the complete period of the measurement, and one or two boats shall move as quickly as possible from vertical to vertical measuring the velocity distribution in the verticals one after another, in the same sequence with intervals of time not greater than 1 h in each vertical. Current velocity graphs for each location at which observations are made shall be inferred for the entire period of observation based on the actually observed values.

Because all these measurements are made simultaneously during the same tidal cycle, they require no extrapolation to other tidal conditions. Furthermore, reference measurements are available for interpolation at the desired points.

c) When the form of the tidal curve does not change significantly from day to day and at least two boats are available for several days, one boat shall be anchored in the middle of the flow at a so-called reference vertical, measuring continuously velocity distribution over the vertical. The other boat shall measure one complete tide in another vertical, the next tide in a following vertical, and so on, until, for every required vertical, a measurement of complete tide is available.

This method needs adjustments to standard tidal conditions, using measurements at the reference vertical. A method of adjusting the observations at the subordinate verticals in relation to the observations at the fixed vertical is indicated in 7.4.

d) When the volume of traffic is large so that it is not possible to anchor a number of boats at the measuring cross-section, a measuring boat shall be anchored at one vertical for one complete tide during which time velocity distribution in the vertical is measured continuously.

This operation shall be repeated at the same vertical for tides of different amplitudes and at other verticals also for a complete range of amplitudes.

Because no reference verticals are available, this method also needs adjustments as indicated in 7.4.4.

To overcome, to a great extent, the difficulties caused by pulsating flow, the following method may be applied when a boat is anchored at one vertical for a complete tide. In the vertical, measurements using a current-meter shall be made continuously by immersing several current-meters at different depths. Readings of the current-meters are to be taken, without stopping them, after each successive period of 10 or 15 min, and the average is to be plotted against the midpoint of the period. The meter at the greatest depth may be mounted on a swivel, supported on a tripod which rests on the bed. The meter nearest to the surface shall be allowed to remain at a fixed distance below the surface.

e) Since oblique flow is unavoidable, the angle of the direction of the flow to the perpendicular to the cross-section shall be measured and the measured velocity corrected. Special instruments have been developed for measuring the angle and velocity at a point simultaneously.

Where, however, these are not available and there is insignificant wind, the angle of flow throughout the vertical may be taken to be the same as that observed on the surface. If the channel is very deep, or if the local bed profile is changing rapidly, this assumption shall not be accepted without checking.

If the measured angle to the perpendicular is γ, then

$$v_{\text{corrected}} = v_{\text{measured}} \cos \gamma$$

7.3.2 *Reduction of the measured velocities in the vertical to the same instant*

Owing to the rapid change of the velocities, the individual measurements in the vertical must be reduced to the same instant in order to obtain the correct velocity distribution over the vertical. The following procedures may be used.

a) The velocities shall be measured at a suitable number of points going from the surface to the bottom, and back again to the surface. Hence, at every point the velocity shall be measured twice, except at the lowest point where the measurement is taken only once. When taking the average of the two measurements at each point, the correct distribution over the vertical shall be found for the moment of the measurement at the lowest point.

b) The velocities shall be measured at a suitable number of points on a vertical, starting from the water surface and proceeding to the bottom. The time of starting the measurement on the vertical shall be noted. The time intervals between successive measurements shall be approximately equal. After the measurement at the lowest point in a vertical, the surface velocity shall be measured a second time. All measurements shall be reduced to the time when the first measurement was taken on the water surface of the vertical, by adding the following correction (negative when the velocity is increasing) :

$$\text{Correction} = \frac{v_1 - v_{1\text{r}}}{v_{1\text{r}}} \times \frac{m_i - 1}{m} \times v_{m_i}$$

where

v_1 is the first measured surface velocity;

$v_{1\text{r}}$ is the second measured surface velocity;

m_i is the serial number of the point in the vertical;

v_{m_i} is the velocity to be corrected;

m is the total number of points in the vertical (see annex A for example).

NOTES

1 It is necessary to measure the direction of flow particularly where there is a salt-water wedge.

2 In order to speed up the measurement of the velocity distribution in a vertical, it is better to reduce the number of points per vertical than to diminish the measuring time in every point of the vertical (pulsations).

3 It is generally not possible to use floats in tidal waters; when a significant salt-water wedge is present, they shall not be used.

4 For extrapolating in the region beyond the last measuring point, the observed velocities at points approaching the bed can be plotted and the smooth curve passing through these points can be extended to the bed. The velocities close to the bed can then be read from this graph.

7.4 Computation of discharge

Depending on the measuring procedure adopted (see 7.3.1), the following methods may be used.

7.4.1 When the velocity distributions are measured simultaneously in all verticals, it is possible to use the methods given in 8.2 of ISO 748, particularly the graphical method or one of the arithmetical methods, to calculate the discharge of the channel at the successive moments of the measurements of the velocity distributions in the verticals. These values of discharge can be used to draw a discharge curve with respect to time, and from this curve, with the aid of a planimeter, the total discharge during the whole ebb-tide (ebb-volume) and the whole flood-tide (flood-volume) can be determined.

7.4.2 When the measurements are not carried out simultaneously, the discharge curve shall be evaluated in the following way :

In every vertical, the mean velocity shall be estimated as specified in 7.3.2. A mean velocity curve against time shall be drawn from each vertical, and from this curve the mean velocity for every desired moment can be read.

With the methods mentioned in 7.4.1, the discharge at a sufficient number of instants can be evaluated and a discharge curve plotted with respect to time.

With a planimeter again the ebb-volume and flood-volume can be determined.

7.4.3 Using the reference-point method with two boats (see 7.3.1c)), various methods for computation of the discharge can be applied, all based on the reduction of one of the relevant quantities to the desired tide within the measuring period. When the tide is not simple harmonic, or changes significantly from day to day, velocities will not necessarily change in proportion to ranges alone. The method then adopted shall be as follows :

For the reference vertical, graphs shall be prepared showing the variation of the average velocity in the vertical with time, during each flood-tide and ebb-tide. Values of the average velocity at a vertical shall be interpolated at each interval of half an hour before and after the time of local high water, and for each time interval these values shall be plotted against the amplitude of the corresponding flood-tide or ebb-tide.

From the series of graphs obtained, mean velocities can be interpolated at each vertical, at a given time relative to that of local high water for a flood-tide or ebb-tide of chosen amplitude.

Where the tides are simple harmonic or do not change significantly from day to day, however, a simpler method is possible, which is to take velocities as proportional to the tidal ranges. The adjustments for the reference vertical shall be made as in table 1, and the adjustments for subordinate verticals shall be made proportionally in the ratio of the ranges.

TABLE 1 — **Adjustment for reference vertical**

Time	Tide range	Observed velocity	Ratio of ranges	Adjusted velocity
H – 1	6,0	3,0 *F*	6,5/6,0	3,2
H	6,0	1,0 *F*	6,5/6,0	1,1
H + 1	6,0	0	6,5/6,0	0
H + 2	7,0	1,0 *E*	6,5/7,0	0,9
–	–	–	–	–
–	–	–	–	–

NOTES

1 The 6,5 range, which was the average of a number of readings, is adopted as the standard range for tide, the range from low water to high water being 6,0 and from high water to low water 7,0.

2 *F* denotes flood-tide and *E* denotes ebb-tide.

3 The figures given in the table may be in either metric or foot-seconds units.

From these interpolated velocities, the spacing of the verticals, and the depth at each vertical, the discharge can be calculated for any phase of any tide and a total discharge curve can be plotted.

7.4.4 When only one boat is available for measurement (see 7.3.1d)), velocity distributions shall be measured at one vertical at a time during a complete tidal cycle, and this shall be repeated for various verticals and various ranges of tide; the value of the mean velocity from the results from each vertical at every hour or half-hour before and after high water shall be plotted against the corresponding range of tide.

Where the tide changes significantly from day to day, graphs shall be prepared showing the variations of average velocity in the vertical with time, and the mean velocity at each vertical at a given time in relation to the time of local high water, for a flood-tide or ebb-tide of chosen range shall be assessed as shown in 7.4.3.

From these mean velocities, the spacing of the verticals, and the depth at each vertical, the discharge can be calculated for any phase of any tide, by reading the graph for some given range of tide, and a total discharge curve can be plotted.

7.4.5 To obtain the total discharge curve in tidal channels when using floats, the following procedure shall be used.

From the obtained velocity distribution curve in each panel, partial discharge curves for each panel can be derived. Addition of these partial discharge curves gives the total discharge curve from which, with the aid of a planimeter, the ebb-volume and flood-volume can be evaluated.

For the reasons given in 6.1 this would, however, give a very approximate result only.

7.4.6 Where proportionality of velocity to tidal range may be assumed from day to day, however, the simpler procedure as illustrated in table 2 may be adopted.

7.5 Additional observation to be taken preferably simultaneously with velocity observation

Measurement of the direction and velocity of wind.

It is important to know the direction and velocity of wind. Ordinary weather vane and anemometer shall be used for this purpose to check that the wind does not affect the velocity measurements.

8 DIRECT MEASUREMENT OF TIDAL FLOW BY THE MOVING-BOAT METHOD

Since the moving-boat method may be applicable in either steady or unsteady flow, it is dealt with in a separate ISO document (in preparation).

9 MEASUREMENT OF TIDAL FLOW BY METHOD OF CUBATURE

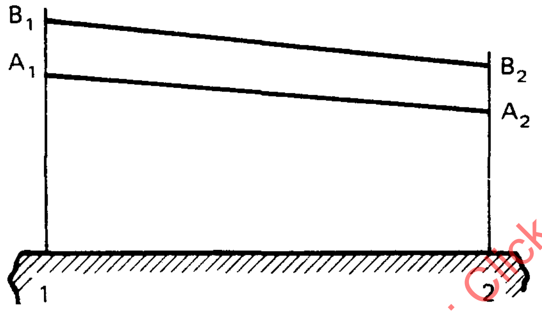

FIGURE — **Water profile between two gauging stations**

9.1 Referring to the figure above, let A_1A_2 and B_1B_2 be the simultaneous water surface levels at the beginning and at the end of the time-interval, between the stations 1 and 2 along the river; that is, at the beginning of the interval the stages at the two stations are A_1 and A_2 and at the end of the interval B_1 and B_2. In the figure, the water profile has risen, representing flooding between the two stations; the profiles could equally as well fall representing ebbing, or cross each other representing a transition. In the latter case, where the profiles cross each other, the method requires an additional station for intermediate data. If there is an upland discharge, it shall be measured separately at a station beyond the reach of the tidal influence. For computing the volume of water flowing seaward at a section, the fresh-water flow over the given time-interval is added to the seaward flow computed from the change in volume of the tidal prism during the same time-interval.

9.2 Computation of the change in the tidal volume between the stations is a straightforward mensuration process :

Let

a_{1-2} be the area of water surface between stations 1 and 2 at the beginning of the time-interval;

a'_{1-2} be the area of water surface between stations 1 and 2 at the end of the time-interval;

L_{1-2} be the distance between stations 1 and 2;

d_1, d_2 be the depth of water at the beginning of the time-interval at stations 1 and 2, respectively;

d'_1, d'_2 be the depth of water at the end of the time-interval at stations 1 and 2 respectively;

TABLE 2

Time	Vertical A, day D_1				Vertical B, day D_2			
	Tide range	**Observed velocity**	**Ratio of ranges**	**Adjusted velocity**	**Tide range**	**Observed velocity**	**Ratio of ranges**	**Adjusted velocity**
H − 1	6,0	3,0 *F*	6,5/6,0	3,2	5,0	2,4 *F*	6,5/5,0	3,1
H	6,0	1,0 *F*	–	1,1	5,0	0,9	–	1,2
H + 1	6,0	0	–	0	5,0	0	–	0
H + 2	7,0	1,0 *E*	6,5/7,0	0,9	5,8	0,8 *E*	6,5/5,8	0,9
–	–	–	–	–	–	–	–	–

NOTES

1 The 6,5 range, which was the average of a number of readings, is adopted as the standard range for tide, the range from low water to high water being 6,0 and from high water to low water 7,0 for day D_1, and these ranges being respectively 5,0 and 5,8 for day D_2

2 *F* denotes flood-tide and *E* denotes ebb-tide.

3 The figures given in the table may be in either metric or foot-second units.

4 The reduction methods given in 7.4.3 and 7.4.4 shall be applied only to the tidal portion of the observed current. All velocities in the flood direction are considered as positive and all velocities in the ebb direction as negative, so that the sign of the result indicates whether there is net flow in the flood or ebb direction. The reduction procedures are first applied to the tidal velocities and the corrected flood and ebb velocities are algebraically added to the non-tidal current.

5 The methods given in 7.4.3 and 7.4.4 shall not be applied when the density of the water at the measuring site varies with time, or when a significant deviation occurs from the astronomical tide due to meteorological influences.

b_1, b_2 be the corresponding river widths at the beginning of the time-interval;

b'_1, b'_2 be the corresponding river widths at the end of the time-interval;

q be the upland discharge;

t be the time-interval.

Then, the change in volume V_{1-2}, according to Pillsbury's method, is given by the formula

$$V_{1-2} = \frac{a_{1-2} + a'_{1-2}}{2} \times \frac{(d'_1 - d_1) + (d'_2 - d_2)}{2} \quad \ldots (1)$$

If the stations are 1, 2, 3 ... up to the tidal limit, the tidal volume flowing V across station 1 in the time-interval in question is : $V = (V_{1-2} + V_{2-3} + \ldots$ up to the tidal limit) $- qt$.

It will be understood that in computing V_{1-2} etc. the correct sign must be used, i.e. + (plus) for flooding and − (minus) for ebbing; in other words, the addition is an algebraic addition. The mean tidal discharge Q_t is obtained by dividing the change in volume by the time-interval, i.e.

$$Q_t = \frac{V}{t} = \frac{1}{t} \Sigma V_{ij} - q$$

9.3 When the river widths do not vary significantly between the two stations and if there are no side storage areas in the entire length, the area of water surface between the two stations can be estimated by Kilford's method :

$$a_{1-2} = \frac{b_1 + b_2}{2} L_{1-2}$$

$$a'_{1-2} = \frac{b'_1 + b'_2}{2} L_{1-2}$$

When substituted in equation (1) this gives

$$V_{1-2} = \frac{L_{1-2}}{8} (b_1 + b_2 + b'_1 + b'_2) (d'_1 + d'_2 - d_1 - d_2) \quad \ldots (2)$$

It will be seen that equation (2) is arithmetically simpler, but it will be satisfactory only when the channel has a prismoidal shape. Equation (1), on the other hand, is more elaborate, but in general more accurate, as it takes areas into account and does not assume uniform variation of sections.

9.4 Determination of the volume of the tide (ebb or flood) can be made by assigning to each time interval the mean discharge Q_t calculated as indicated in 9.2; the total volume discharged during the entire ebb-tide or flood-tide is :

$$V_m = \Sigma Q_t t = \Sigma(\Sigma V_{ij} - qt)$$

the summation ranging from the low-water slack to the high-water slack or vice-versa.

9.5 Typical illustrations of the use of equations (1) and (2) are given in annexes B and C respectively. As described in 5.3 the cubature computation will proceed from the head of the estuary (tidal limit) to the mouth (or the particular cross-section).

10 ERRORS IN TIDAL FLOW MEASUREMENT

The following is a general expression of the calculation of errors. It is to be noted that in due course it is hoped that an International Standard will be available in which a uniform approach to the calculation of uncertainties will be provided, but in the meantime, the following may be used.

10.1 Errors in direct measurement of tidal flow

Reference is made to clause 9 of ISO 748. The necessary definitions and a general outline on the method of error calculation are given in that clause. These only give the necessary extensions for application to tidal flow measurements. Estimates of the magnitude of the additional error components cannot be given as yet.

10.1.1 *Sources of error*

The generalized form, given in 9.1.2 of ISO 748 for determining the discharge Q, shall be extended to read :

$$Q_t = \sum_{i=1}^{i=m} \left(b_i d_i \bar{v}_i \cos \bar{\varphi}_i\right)_t$$

where

Q_t is the discharge at one particular moment of the tidal cycle;

$\bar{\varphi}_i$ is the mean in a vertical of the angles φ between the single measured velocity and the normal to the cross-section.

The overall error in the tidal (ebb or flood) volume is then composed of the following errors expressed as percentage random standard errors.

a) Errors in width.

b) Errors in depth, both of individual soundings and readings of the water level.

These shall be determined having regard to 6.2.3 of ISO 748.

NOTE — Errors originating from the variation of depth and width with time may usually be neglected.

c) Errors in the determination of individual velocities.

These will depend on the accuracy of the apparatus, on the technique employed (see 7.1.1, 7.1.5 and 7.2.5 of ISO 748), on the irregularity of the velocity distribution with time and space, and on the magnitude of $d\bar{v}_i/dt$, being the rate of change of the average velocity $\bar{v}_i$ with time.

NOTE — These errors occur particularly during the slack-water period due to the limitation of the current-meter in measuring velocities below 0,15 m/s.

d) Errors in the use of the velocity-area method, particularly those concerned with the number of verticals and the number of points in each vertical.

These errors will also depend on the width of the channel, the ratio of width and depth, and on the method of computation used.

e) Errors in the determination of the angle (in a horizontal plane) between the single velocity vector and the normal to the cross-section.

f) Errors due to the reduction of the individual measurements in the vertical to the same instant.

g) Errors arising from interpolation to the same instant of mean velocities in the vertical, in cases where the velocity distributions are not measured simultaneously.

h) Errors arising from the reduction of mean velocities from one tide to another tide.

10.1.2 *Individual components of errors*

In 9.1.3 of ISO 748 the following components have been mentioned and remain substantially the same :

- errors in width (X'_{b_i});
- errors in depth (X'_{d_i});
- errors in the determination of local point velocities (X'_v);
- errors in the determination of the mean velocities, composed of :

  a) number of points (X'_o);

  b) mean velocity in a vertical ($X'_{\bar{v}_i}$), to be derived from

$$X'_{\bar{v}_i} = \sqrt{X'^2_{\bar{v}} + X'^2_o}$$

  c) number of verticals (X'_m).

To these components the following have to be added for tidal flow :

- errors in the mean of the angles between the velocity-vectors and the normal to the cross-section ($X'_{\bar{\varphi}}$).

If X'_φ is the error in the angle of a single velocity then the error $X'_{\bar{\varphi}}$ for a vertical is to be determined from

$$X'_{\bar{\varphi}} = \sqrt{\frac{\Sigma X'^2_\varphi}{m}}$$

where m is the number of velocities measured in the vertical.

- errors arising from insufficiencies in the applied method (X'_s).

Under this heading are considered the errors mentioned under f), g) and h) of 10.1.1, and indicated by $X'_{(i)}$, $X'_{(ii)}$, and $X'_{(iii)}$, respectively. X'_s is to be determined from

$$X'_s = \sqrt{X'^2_{(i)} + X'^2_{(ii)} + X'^2_{(iii)}}$$

Each of the constituent errors in this formula may be left out when not applicable. $X'_{(i)}$ is usually negligible. $X'_{(iii)}$ may be large; this implies that the method it arises from should only be used if $X'_{(iii)}$ is known. $X'_{(ii)}$ is to be derived from :

$$X'_{(ii)} = X'_{\bar{v}_t} = X'_t \frac{d\bar{v}}{dt}$$

where

$X'_{\bar{v}_t}$ is the error in the mean velocity $\bar{v}$ of a vertical for which $\bar{v}$ has been determined by interpolation;

X'_t is the error of time measurement (percentage error relative to the time-interval between measurements of verticals, and due to synchronization of watches, etc.);

$\frac{d\bar{v}}{dt}$ is the slope of the velocity-time curve.

- The error arising from taking "limited number" of discharge measurements during the tidal period can be disregarded.

10.1.3 *Resultant random standard error in measurement of flow*

The percentage resultant random standard error X'_{Q_t} in measurement of flow at time t shall be calculated according to the first equation in 9.1.4 a) of ISO 748, completed as follows :

$$X'_{Q_t} = \sqrt{X'^2_m + \frac{\sum_{i=1}^{i=m} \left[\left(b_i d_i \bar{v}_i \cos\bar{\varphi}_i\right)^2 \left(X'^2_{b_i} + X'^2_{d_i} + X'^2_{\bar{v}_i} + X'_{\bar{\varphi}_i} \tan^2\bar{\varphi}_i\right)\right]_t}{\sum_{i=1}^{i=m}\left(b_i d_i \bar{v}_i \cos\bar{\varphi}_i\right)^2_t} + X'^2_s}$$

The use of a simplified formula based on the second equation in clause 9.1.4 a) of ISO 748 is not recommended.

10.1.4 *Resultant systematic standard error in measurement of flow*

The above equations are satisfactory for estimating the precision of the measurement but do not take account of the possibility of systematic errors. Systematic errors which behave as random errors shall be estimated separately and may be combined as follows :

$$X''_Q = \sqrt{X''^2_b + X''^2_d + X''^2_{\overline{v}} + X''^2_{\overline{\varphi}}}$$

where X''_b, X''_d, $X''_{\overline{v}}$ and $X''_{\overline{\varphi}}$ are the percentage systematic standard errors in b, d, $\overline{v}$ and $\overline{\varphi}$ respectively.

NOTE — It is a question here of systematic errors due to the instruments, which vary randomly from instrument to instrument, and not of systematic errors inherent in the type of instrument or measurement which can be eliminated or determined only if a superior instrument or improved method is available.

10.1.5 *Combined standard error in the measurement of flow*

The overall estimate of the standard error of the discharge will then be

$$X_{Q_t} = \sqrt{X'^{\,2}_{Q_t} + X''^{\,2}_Q}$$

This value shall be doubled to give the tolerance on the measurement of the discharge, as indicated in 9.1.1 of ISO 748.

10.1.6 *Combined standard error in the determination of the tidal (ebb or flood) volume*

If S_{vol} and S_{Q_t} are, in absolute value, the standard errors in the measurements of the tidal volume and discharge respectively ($S_{Q_t} = Q_t X_{Q_t}$), and if T is the constant time-interval between successive moments p at which Q_t is determined

$$S_{vol} = T\sqrt{\sum_{i=1}^{i=p} S^2_{Q_{t_i}}}$$

This value shall be doubled to give the tolerance, in absolute value, on the determination of the tidal volume, as indicated in 9.1.1 of ISO 748.

10.2 Errors in measurement of tidal flow by the method of cubature

10.2.1 *Sources of errors*

Errors which affect the method of cubature are of two kinds : in the first instance, errors occur in the determination of the volume of each one of the elementary prisms; they are essentially errors of measurement and errors due to the method of calculation (see 10.2.2); at a later stage errors occur in the determination of the flow, which are due to the very principle and conditions of application of the method (see 10.2.3).

The cubature method is specially suitable in the case of rivers which have a large number of gauge stations, preferably along both banks, so that water levels can be accurately computed by interpolation to account for discontinuities and irregularities and effects due to change in channel width, curvatures, wind effects. Thus, for this method, gauges shall be installed at sufficiently small intervals, that is, in large estuaries, not more than 8 km apart.

10.2.2 *Errors in the determination of the volume of elementary prisms*

Of the two methods of cubature described respectively in 9.2 and 9.3, it may be mentioned that the method described in 9.3 (Kilford's method) is simpler, but permissible only if the river width varies uniformly between successive stations. With the usual form of a stream where the width is irregular, the method described in 9.2 (Pillsbury's method) would yield more accurate results and hence is preferable.

10.2.2.1 INDIVIDUAL COMPONENTS OF THE ERROR

The error in the volume of the elementary prisms consists of the following individual errors :

a) error in the variation of depth ($X_{\Delta d_i}$) : it shall be calculated by comparing the absolute value of the error with the depth variation $\Delta d_i = d'_i - d_i$ between the start and end of the time-interval;

b) error in width (X_{b_i}) and in the distance between sections ($X_{L_{ij}}$) : these two sources of error occur directly only in Kilford's method;

c) error in the area of the water surface ($X_{a_{ij}}$) : it is the inaccuracy due to the curve connecting this area to the water level, and therefore to the topographical elements which have permitted its determination; this error occurs only in Pillsbury's method;

d) error due to the method of calculation (X_c) : it is the error that is committed while comparing the volume of water comprised between sections i and j and the water surfaces, at the beginning and end of the time-interval with a prism of simple geometrical shape.

10.2.2.2 RESULTANT RANDOM STANDARD ERROR IN THE VOLUME OF THE PRISM

If $X'_{\Delta d_i}$, X'_{b_i}, $X'_{L_{ij}}$, $X'_{a_{ij}}$ and X'_c are, in percent, the random standard errors due to each one of the components listed in 10.2.2.1, the resultant random standard error $X'_{V_{ij}}$, in percent, in the volume of an elementary prism is calculated as follows, whether the formula in clause 9.2 or clause 9.3 is used :

— with Pillsbury's method (see 9.2)

$$X'_{V_{ij}} = \sqrt{\frac{1}{2}X'^{\,2}_{a_{ij}} + \frac{1}{2}X'^{\,2}_{\Delta d_i} + X'^2_c}$$

– with Kilford's method (see 9.3)

$$X'_{V_{ij}} = \sqrt{X'^{\,2}_{L_{ij}} + \frac{1}{4}X'^{\,2}_{b_i} + \frac{1}{2}X'^{\,2}_{\Delta d_i} + X'^{2}_{c}}$$

NOTE – The same mean values of $X'_{a_{ij}}$, $X'_{\Delta d_i}$ and X'_{b_i} are allowed at the different moments and in the different sections, and it is supposed that the areas and variations in depth and widths are respectively very slightly different between them.

10.2.2.3 Resultant systematic standard error in the volume of the prism

Systematic errors which behave like random errors shall be determined separately and can be combined as follows :

– with Pillsbury's method (see 9.2)

$$X''_{V} = \sqrt{\frac{1}{2}X''^{2}_{a} + \frac{1}{2}X''^{\,2}_{\Delta d}}$$

– with Kilford's method (see 9.3)

$$X''_{V} = \sqrt{X''^{2}_{L} + \frac{1}{4}X''^{2}_{b} + \frac{1}{2}X''^{\,2}_{\Delta d}}$$

where $X''_{\Delta d}$, X''_{b}, X''_{L} and X''_{a} are, in percent, the systematic standard errors on Δd, b, L and a, respectively.

NOTE – It is a question here of systematic errors due to the instruments, but which vary randomly from instrument to instrument, and not of systematic errors inherent in the type of instrument or measurement which could be eliminated or determined only if a better apparatus or a better method was available.

10.2.3 *Errors in the determination of flow*

10.2.3.1 Errors in time

a) Errors in time – Measurements

The accuracy of this method depends on how accurately the simultaneous gauge curves represent the actual instantaneous water profiles in the river. An error in the simultaneous observations, i.e. a difference in time of the observations, would cause an error in the measurement of profiles. It is, therefore, desirable that the observations at the various gauges be observed at precisely the same times, say, at half-hourly intervals. Automatic recorders duly synchronised would considerably reduce the subjective error due to non-synchronous observations as well as ensuring that the high-water and low-water levels are not missed.

With visual readings the accuracy can be improved by greater accuracy of observations.

b) Errors in time – Computations

The computation is based on series of straight line steps of the storage curve, each step being the interval between two consecutive computations. Care shall be taken to see that the time interval is sufficient, but on the other hand not excessive, to represent a close approximation to the actual storage curve.

10.2.3.2 Errors caused by density currents

The cubature method would give an entirely erroneous measure of the tidal flow in one direction when there is a density current or where part of the flow is in one direction and part in another, because this method measures only the profile of the water area.

10.2.3.3 Errors due to intervening tributaries and bifurcations

If a tributary falls within a cubature section, or if the cubature section is bifurcated into more than one tidal channel, separate computation has to be made at the same intervals of time for the inlet or the outlet channel. The area between two adjacent cubature stations shall include any minor tidal tributary entering the section, unless a separate cubature was computed for the tributary.

If the arms of bifurcations have direct outlets to the sea then the cubature method is inapplicable below the bifurcation.

10.2.3.4 Errors due to turn of the tide

The cubature method assumes that the water level at two adjoining stations is simultaneously rising or falling. If the water level at one of the stations is rising while at the other station it is falling, such a reach has to be subdivided into two at the point of high water or low water and the same procedure repeated. This will introduce a subjective error of judgement in the interpolation which can be reduced by repetition by more than one observer.

10.2.3.5 Overall random standard error in the measurement of flow

According to 9.2, the mean discharge Q during a time interval t is equal to :

$$Q = \frac{1}{t}\Sigma V_{ij} - q$$

If X'_t, $X'_{V_{ij}}$ and X'_q are, in percent, the random standard errors on t, V_{ij} (calculated as in 10.2.2.2) and q respectively, and if X'_s is the random standard error arising from the insufficiencies (resulting from the errors mentioned in 10.2.3.1 to 10.2.3.4), the overall random standard error X'_Q on the measurement of discharge, in percent, is

$$X'_Q = \sqrt{\frac{\sum\left(\frac{1}{t}V_{ij}\right)^2\left(X'^2_t + X'^{\,2}_{V_{ij}}\right) + q^2 X'^2_q}{\left(\sum \frac{1}{t}V_{ij} - q\right)^2} + X'^2_s}$$

10.2.3.6 OVERALL SYSTEMATIC STANDARD ERROR IN THE MEASUREMENT OF DISCHARGE

Systematic errors which behave like random errors shall be determined separately and can be combined as follows :

$$X''_Q = \sqrt{\frac{\sum\left(\frac{1}{t}V_{ij}\right)^2\left(X''^2_t + X''^2_V\right) + q^2 X''^2_q}{\left(\sum\frac{1}{t}V_{ij} - q\right)^2}}$$

where X''_t, X''_V and X''_q are, in percent, the systematic standard errors on t, V (as calculated as in 10.2.2.3) and q respectively.

NOTE — It is a question here of systematic errors due to the instruments, but which vary randomly from instrument to instrument, and not of systematic errors inherent in the type of instrument or measurement which could be eliminated or determined only if a better apparatus or a better method was available.

10.2.3.7 COMBINED STANDARD ERROR IN THE MEASUREMENT OF DISCHARGE

The overall estimation of the standard error on the discharge will then be :

$$X_Q = \sqrt{X'^2_Q + X''^2_Q}$$

This value shall be doubled to obtain the tolerance on the measurement of the discharge as stated in 9.1.1 of ISO 748.

10.2.4 *Combined standard error in the determination of the tidal (ebb or flood) volume*

Even though the discharge step is not necessary, in the cubature method, to calculate the total volume of the tide, the error in the latter is expressed more simply on the basis of the error on the discharge.

If S_{vol} and S_Q are, in absolute value, the standard errors in the measurements of the volume of the tide and of the discharge and if t is the constant time-interval between two successive readings (see 9.4)

$$S_{vol} = t\sqrt{\Sigma S_Q{}^2}$$

or, by using the standard errors X_{vol} and X_Q expressed as percentages, and if we assume that X_Q remains constant :

$$X_{vol} = \frac{\sqrt{\Sigma Q^2}}{\Sigma Q} X_Q$$

These values shall be doubled in order to obtain the tolerance on the determination of the volume of the tide as stated in 9.1.1 of ISO 748.

10.3 Cross-checking between method of direction measurement and measurement by cubature

It is desirable, wherever practicable, to cross-check the results of the measurements by one method against the measurement of the other, i.e. between the direct and indirect methods of measurement of tidal flow.