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Liquid flow measurement in open channels — Round-nose horizontal broad-crested weirs

Mesure de débit des liquides dans les canaux découverts — Déversoirs horizontaux à seuil épais arrondi

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

International Standard ISO 4374 was prepared by Technical Committee ISO/TC 113, *Measurement of liquid flow in open channels*.

This second edition cancels and replaces the first edition (ISO 4374 : 1982), of which it constitutes a technical revision.

Annexes A, B and C form an integral part of this International Standard.

NOTE — Guidelines for the selection of weirs and flumes for the measurement of the discharge of water in open channels are given in ISO 8368 : 1985, *Liquid flow measurement in open channels — Guidelines for the selection of flow gauging structures.*

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Liquid flow measurement in open channels — Round-nose horizontal broad-crested weirs

1 Scope

1.1 This International Standard deals with the measurement of flow in rivers and artificial channels under steady flow conditions using round-nose horizontal broad-crested weirs (see figures 1 and 2).

1.2 The flow conditions considered are limited to steady flows which are uniquely dependent on the upstream head. Drowned flows, which depend on downstream as well as upstream levels, are not covered by this International Standard.

1.3 The round-nose horizontal broad-crested weir has a good discharge range and modular limit and is appropriate for use in small- and medium-sized installations. It is particularly robust and insensitive to minor damage.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 772 : 1988, *Liquid flow measurement in open channels — Vocabulary and symbols.*

ISO 5168 : 1978, *Measurement of fluid flow — Estimation of uncertainty of a flow-rate measurement.*

3 Definitions and symbols

For the purposes of this International Standard, the definitions given in ISO 772 apply. A full list of symbols with the corresponding units of measurement is given in annex A.

4 Installation

4.1 Selection of site

4.1.1 The weir shall be located in a straight section of channel, avoiding local obstructions, roughness or unevenness of the bed.

4.1.2 A preliminary study shall be made of the physical and hydraulic features of the proposed site, to check that it conforms (or can be made to conform) to the requirements necessary for measurement of discharge by the weir. Particular attention should be paid to the following features in selecting the site:

a) the adequacy of the length of channel of regular cross-section available (see 4.2.2.2);

b) the uniformity of the existing velocity distribution (see annex B);

c) the avoidance of a steep channel (but see 4.2.2.6);

d) the effects of any increased upstream water level due to the measuring structure;

e) the conditions downstream (including influences such as tides, confluences with other streams, sluice gates, mill dams and other controlling features which might cause drowning);

f) the impermeability of the ground on which the structure is to be founded and the necessity for piling, grouting or other means of controlling seepage;

g) the necessity for flood banks, to confine the maximum discharge to the channel;

h) the stability of the banks, and the necessity for trimming and/or revetment in natural channels;

i) the uniformity of the cross-section of the approach channel;

j) the prevailing wind, which can have a considerable effect on the flow in a river, or over a weir or flume, especially when the river, weir or flume is wide and the head is small and when the prevailing wind is in a transverse direction;

k) aquatic weed growth;

l) sediment transportation.

4.1.3 If the site does not possess the characteristics necessary for satisfactory measurements, or if an inspection of the stream shows that the velocity distribution in the approach channel deviates appreciably from the examples described in annex B, the site shall not be used unless suitable improvements are practicable. Alternatively, the performance of the installation may be checked by independent flow measurements.

4.2 Installation conditions

4.2.1 General requirements

4.2.1.1 The complete measuring installation consists of an approach channel, a weir structure and a downstream channel. The condition of each of these three components affects the overall accuracy of the measurements. Installation requirements include features such as the surface finish of the weir, the cross-sectional shape of the channel, the channel roughness and the influence of control devices upstream or downstream of the gauging structure.

4.2.1.2 The distribution and direction of velocity may have an important influence on the performance of a weir (see 4.2.2 and annex B).

4.2.1.3 Once a weir has been installed, any changes in the systems which affect the basis of the design will alter the discharge characteristics.

4.2.2 Approach channel

4.2.2.1 If the flow in the approach channel is disturbed by irregularities in the boundary, for example by large boulders or rock outcrops, or by a bend, sluice gate or other feature which causes asymmetry of discharge across the channel, the accuracy of gauging may be significantly affected. The flow in the approach channel shall have a symmetrical velocity distribution (see annex B) and this can most readily be achieved by providing a long straight approach channel of uniform cross-section.

4.2.2.2 A length of straight approach channel equal to five times the water-surface width at maximum flow will usually suffice, provided that flow does not enter the approach channel with high velocity via a sharp bend or angled sluice gate. However, a greater length of uniform approach channel is desirable if it can readily be provided.

4.2.2.3 The length of uniform approach channel suggested in 4.2.2.2 refers to the distance upstream of the head measuring position. However, in a natural channel it would be uneconomic to line the bed and banks with concrete for this distance, and it would be necessary to provide a contraction in plan if the width between the vertical walls of the lined approach to the weir is less than the width of the natural channel. The unlined channel upstream of the contraction shall nevertheless comply with the requirements of 4.2.2.1 and 4.2.2.2.

4.2.2.4 Vertical side walls to effect a contraction in plan shall be symmetrically disposed with respect to the centreline of the channel and shall preferably be curved with a radius R of not less than $2H_{max}$. The downstream tangent point shall be at least H_{max} upstream of the head measurement section. The height of the side walls shall be chosen such that the design maximum discharge can be contained.

4.2.2.5 In a channel where the flow is free from floating and suspended debris, good approach conditions can also be provided by suitably placed baffles formed of vertical laths, but no baffle shall be nearer to the point at which the head is measured than a distance of $10H_{max}$.

4.2.2.6 Under certain conditions, a hydraulic jump may occur upstream of the measuring structure, for example if the approach channel is steep. Provided that the hydraulic jump is at a distance upstream of not less than about $30H_{max}$, flow measurement will be feasible, subject to confirmation that an even velocity distribution exists at the gauging station.

4.2.2.7 Conditions in the approach channel can be verified by visual inspection or measurement for which several methods are available such as current-meters, floats, velocity rods, and concentrations of dye, the last being useful to check conditions at the bottom of the channel. A complete and quantitative assessment of velocity distribution may be made by means of a current-meter. The velocity distribution should then be assessed by reference to annex B.

4.3 Weir structure

4.3.1 The structure shall be rigid and watertight and capable of withstanding flood flow conditions without damage from outflanking or from downstream erosion. The weir crest shall be at right angles to the direction of flow and the geometry shall conform to the dimensions given in the relevant clauses.

4.3.2 The surfaces of the weir and of the vertical abutments flanking the weir shall be smooth; they may be constructed in concrete with a smooth cement finish, or surfaced with a smooth non-corrodible material. In laboratory installations, the finish shall be equivalent to that of rolled sheet metal or planed, sanded and painted timber. The surface finish is of particular importance on the horizontal crest, but the requirements may be relaxed beyond a distance along the profile $1/2H_{max}$ upstream and downstream of the crest profile.

4.3.3 In order to minimize errors in the discharge measurements, the following tolerances should be aimed at during construction:

— on the crest width, 0,2 % of this width with a maximum of 0,01 m;

— on the horizontal surfaces, slopes of 0,1 % (1 mm/m).

The structure shall be measured on completion of construction and at regular intervals thereafter and if it varies from the design dimensions by more than the permissible tolerances, the discharge shall be re-computed.

4.4 Movable measuring structure

4.4.1 For water management purposes, it is in many cases necessary to measure flows and also to control water levels or flow at the same location. A combined measuring and regulating structure provides the most economic means for this purpose. The movable round-nose horizontal broad-crested weir may be constructed with one single vertical slot in which the supporting plate of the weir crest can be raised or lowered according to the desired crest level. A vertical guide wall, founded on the bed of the channel and parallel to the supporting plate, acts as a watertight barrier for the movable weir.

4.4.2 If regular sediment flushing is expected to be necessary, the weir may be constructed with two slots. The movable weir is placed in the downstream slot while a bottom gate is placed in the upstream slot. During flow measurement, the bottom gate is lowered onto the bed. To flush sediment that has settled upstream of the weir, the bottom gate is opened by connecting it to the movable weir and raising the weir and gate together.

4.4.3 The most commonly used type of movable weir is that with two vertical slots. This telescopic weir consists of two sliding blades and a movable weir which are mounted on a steel guide frame in the following manner.

a) The bottom gate is blocked in place under operational conditions and acts as a bottom limiter for the movable weir.

b) The upper slide is connected to the bottom gate by means of two steel strips placed in the frame grooves and acts as a top limiter for the movable weir.

c) The movable weir is connected by two steel strips to a horizontal lifting beam. The weir crest is horizontal in both directions. The upstream nose of the weir is rounded off in such a way that flow separation does not occur.

Figure 2 shows the round-nose horizontal broad-crested weir as a measuring and regulating structure.

4.5 Downstream conditions

Conditions downstream of the structure are important in that they control the tail-water level. This level is one of the factors which determines whether modular or drowned flow conditions will occur at the weir. It is essential, therefore, to calculate or observe tail-water levels over the full discharge range and to make decisions regarding the type of weir and its required geometry in the light of this evidence.

5 Maintenance — General requirements

Maintenance of the measuring structure and the approach channel is important to secure accurate and continuous measurements. It is essential that the approach channel be kept clean and free from silt and vegetation as far as practicable for the minimum distance specified in 4.2.2.2. The float well and the entry from the approach channel shall also be kept clean and free from deposits.

The weir structure shall be kept clean and free from clinging debris and care shall be taken in the process of cleaning to avoid damage to the weir crest.

6 Measurement of head

6.1 General requirements

6.1.1 Where spot measurements are required, the head upstream of the weir crest can be measured using a vertical or inclined gauge, a hook gauge, point gauge, wire weight gauge or tape gauge. Where a continuous record is required, a recording gauge shall be used. The location of the head measurement section is dealt with in 7.2.

6.1.2 With decreasing size of the weir and the head, small errors in construction and in the zero setting and reading of the head measuring devices become of greater relative importance.

6.2 Gauge well

6.2.1 It is usual to measure the head in a separate gauge well to reduce the effects of water-surface irregularities. When this is done, it is also desirable to measure the head in the approach channel as a check.

6.2.2 The gauge well shall be vertical and of sufficient height and/or depth to cover the full range of water levels, and shall have a minimum height of 0,3 m above the maximum water level estimated. At the recommended position for the measurement of head, the well shall be connected to the approach channel by means of a pipe or slot.

6.2.3 Both the well and the connecting pipe or slot shall be watertight, and where the well is provided for the accommodation of the float of a level recorder, it shall be of adequate size and depth to give clearance around the float at all stages. The float shall not be nearer than 0,075 m to the wall of the well.

6.2.4 The pipe or slot shall have its invert not less than 0,06 m below the lowest level to be gauged, and it shall terminate flush with the boundary of the approach channel and at right angles thereto. The approach channel boundary shall be plain and smooth (equivalent to carefully finished concrete) within a distance of 10 times the diameter of the pipe or width of slot from the centreline of the connection. The pipe may be oblique to the wall only if it is fitted with a removable cap or plate, set flush with the wall, through which a number of holes are drilled. The edges of those holes shall not be rounded or burred.

6.2.5 Adequate additional depth shall be provided in the well to avoid the danger of the float grounding on the bottom or on any accumulation of silt or debris. The gauge well arrangement may include an intermediate chamber of similar size and proportions between it and the approach channel, to enable silt and other debris to settle out where they may be readily seen and removed.

6.2.6 The diameter of the connecting pipe or width of slot shall be sufficient to permit the water level in the well to follow the rise and fall of head without appreciable delay, but it should be as small as possible, consistent with ease of maintenance, to damp out oscillations due to short-period waves.

6.2.7 No firm rule can be laid down for determining the size of the connecting pipe or slot, because this is dependent on the circumstances of the particular installation, for example whether the site is exposed and thus subject to waves, and whether a large diameter well is required to house the floats of recorders. It is preferable to make the connection too large, rather than too small, because a restriction can easily be added later if short-period waves are not adequately damped out. A pipe 100 mm in diameter is usually suitable for flow measurement in the field. A diameter of 3 mm may be appropriate for precision head measurement with steady flows in the laboratory.

6.3 Zero setting

6.3.1 Initial accurate setting of the zero of the head measuring device with respect to the crest level of the weir, and regular checking of this setting thereafter, are essential if overall accuracy is to be attained.

6.3.2 An accurate means of checking the zero shall be provided. The instrument zero shall be obtained by direct reference to the weir crest, and a record shall be made of the settings carried out in the approach channel and in the gauge well. A zero check based on the water level (when the flow either ceases or just begins) is liable to serious errors due to surface tension effects and shall not be used.

6.3.3 In the case of a movable weir both the upstream water level and the crest level vary. The elevation of the crestline can be read from a fixed gauge. A typical method for measuring the elevation of the crestline is by the installation of this gauge, fixed at the abutment and parallel to the lifting beam on which a horizontal strip indicates the elevation of the crest.

The weir is brought to a certain level. The reading of the fixed gauge on the abutment is recorded, and the zero setting described in 6.3.2 can be carried out.

A direct reading can be obtained by constructing the stilling well close to the lifting beam. The gauge is connected to the lifting beam so that it moves in the stilling well, while its zero coincides with the elevation of the vertexline. This method can also be applied for continuous recording.

7 Round-nose horizontal broad-crested weirs

7.1 Definition

7.1.1 The standard weir comprises a truly level and horizontal crest, between abutments. The upstream edge shall be rounded in such a manner that flow separation does not occur, and downstream of the horizontal crest there shall be either

a) a rounded edge,

b) a downward slope, or

c) a vertical face.

The weir shall be set at right angles to the direction of flow in the approach channel.

7.1.2 The dimensions of the weir and its abutments shall comply with the requirements indicated in figure 1. The radius, r, of the upstream crest shall not be less than 0,2 H_{max}. The length of the horizontal portion of the weir crest shall not be less than 1,75H_{max} nor should the sum of the crest length and nose radius be less than 2,25H_{max}.

7.1.3 In the case of a movable weir, the weir body may be made of steel or aluminium metal plate. If the weir has a fixed crest then it may be made of metal plate or of well-finished concrete.

If the structure has to be used to regulate and to measure flows, which is often the case for weirs used for irrigation purposes, then the construction will take the form of a vertical sliding overflow structure, movable by hand or mechanically.

7.2 Location of head measurement section

7.2.1 The head on the weir shall be measured at a point far enough upstream of the crest to be clear of the effects of drawdown, but close enough to the weir to ensure that the energy loss between the section of measurement and the upstream edge of the weir crest can be considered to be negligible. It is recommended that the head measurement section be located a distance of between three and four times H_{max} upstream of the weir block.

7.2.2 The crest height, if movable, shall be measured simultaneously with the upstream water level (see 6.3.3).

The head, h, (see figure 1) shall be determined within an absolute accuracy of a few millimetres (see 9.2). Regular inspection and maintenance of the whole structure is therefore indispensable.

7.3 Provision for modular flow

Flow is modular when it is independent of variations in tail-water level. For this to occur, assuming subcritical conditions in the tail-water channel, the tail-water total head level must not rise beyond a certain percentage of H. If the downstream face of the weir is vertical, this percentage is dependent on H/p_d: it is 63 % for low values of H/p_d, rising to 75 % at H/p_d = 0,5 and 80 % at $H/p_d \geqslant 1$. These values also apply to a movable weir structure. If the weir block has a downstream slope flatter than 1 in 5, the modular limit may be taken as 5 % higher throughout. In the above, p_d is the height of the crest above the downstream bed level.

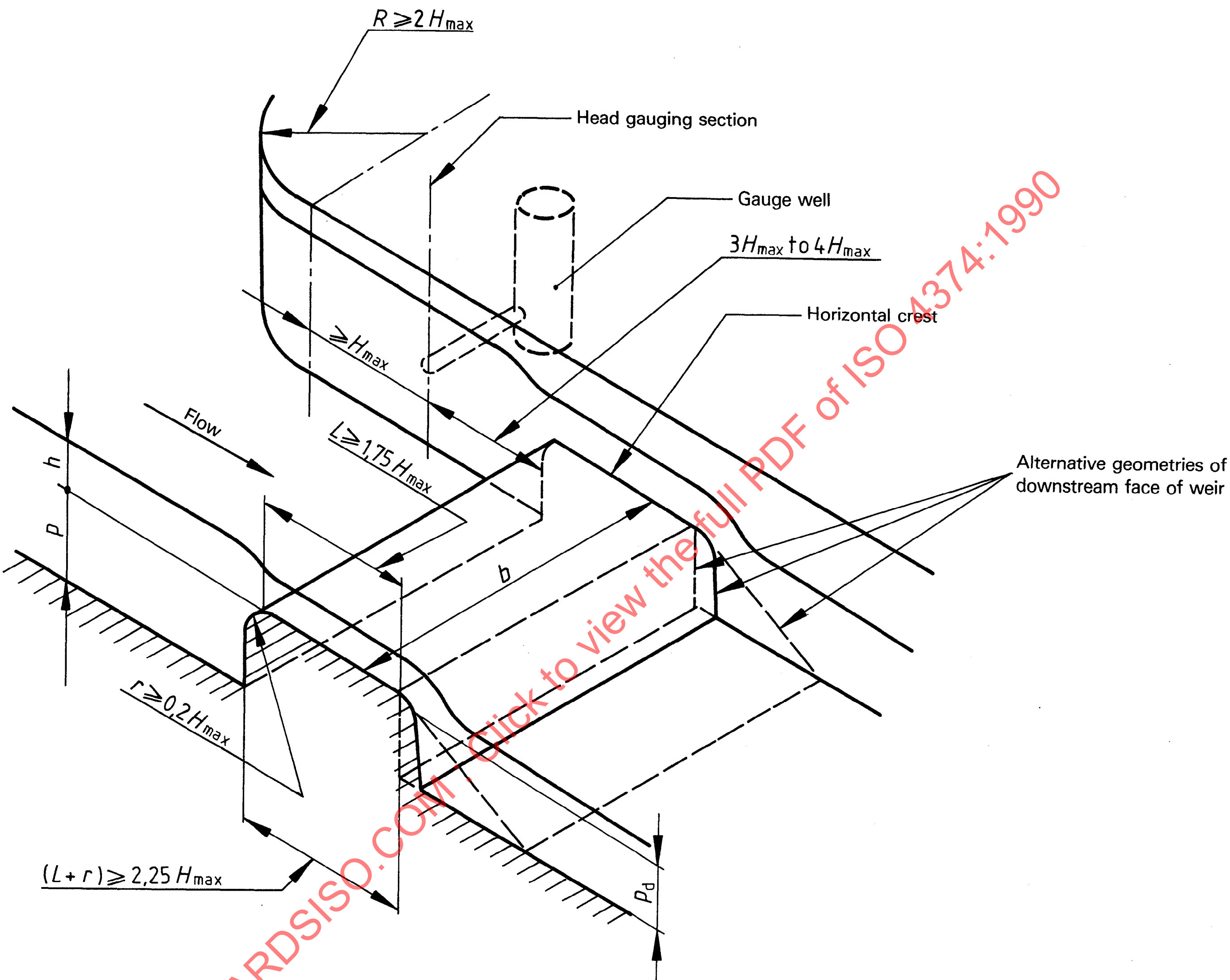

Figure 1 — Round-nose horizontal broad-crested weir — General arrangement

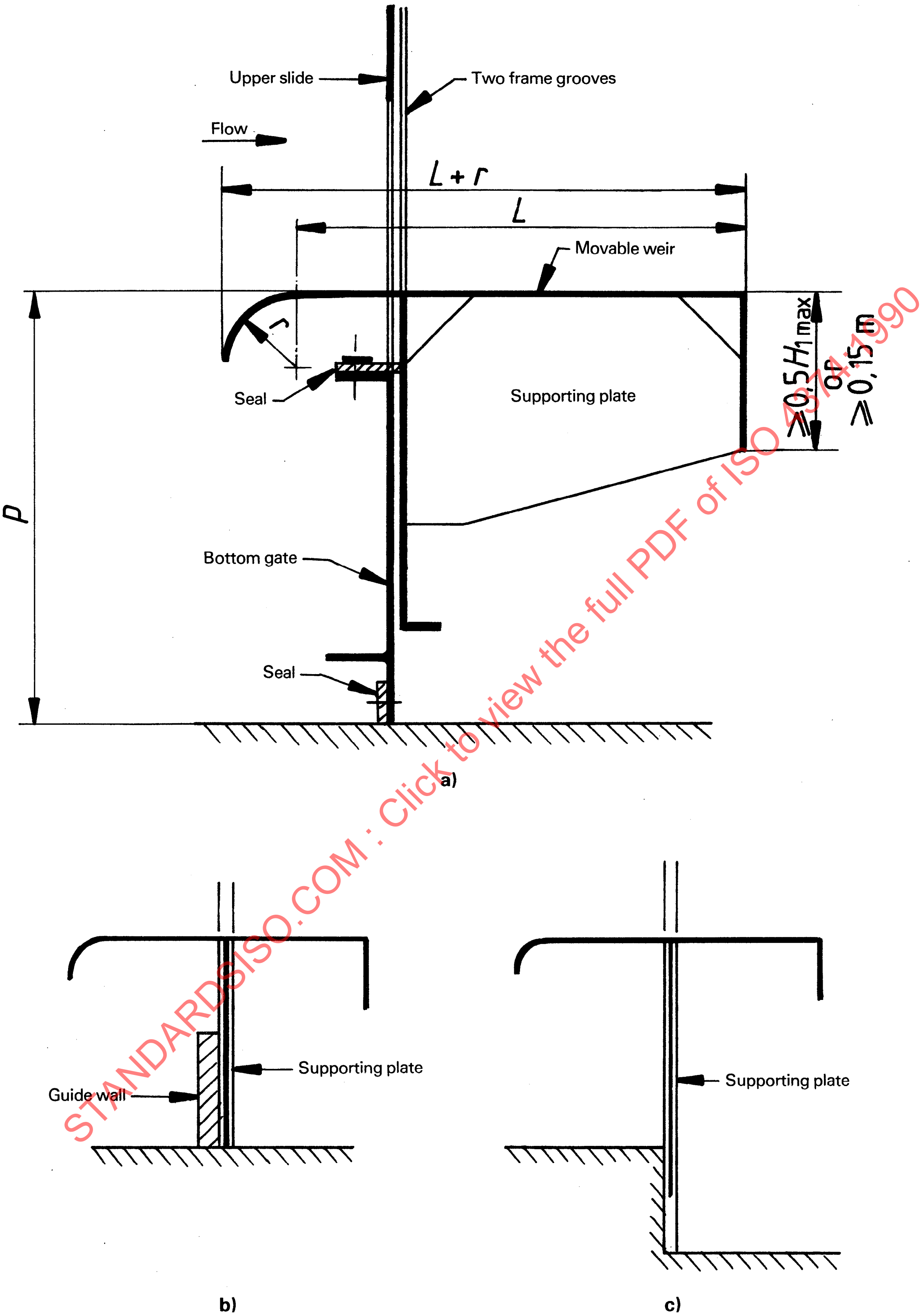

Figure 2 — Combined measuring and regulating structure of a round-nose horizontal broad-crested weir

8 Discharge equations

8.1 Basic equation

8.1.1 Critical depth theory, augmented by experimental data, has shown that the discharge, Q, over a round-nose horizontal broad-crested weir may be represented by the following equation:

$$Q = \left(\frac{2}{3}\right)^{3/2} C_D \, b \sqrt{g} \, H^{3/2} \quad \ldots (1)$$

where

C_D is the coefficient of discharge (non-dimensional);

b is the width of the weir crest;

g is the gravitational acceleration;

H is the total head.

8.1.2 Since the total head, H, cannot be measured directly, the discharge equation in terms of the gauged head, h, relative to crest level, may be written as follows:

$$Q = \left(\frac{2}{3}\right)^{3/2} C_D \, C_v \, b \sqrt{g} \, h^{3/2} \quad \ldots (2)$$

where C_v is a further dimensionless coefficient allowing for the effect of approach velocity on the measured water level upstream of the weir.

By definition

$$C_v = \left(\frac{H}{h}\right)^{3/2} \quad \ldots (3)$$

8.1.3 The total head is related to the gauged head by the equation

$$H = h + \alpha \bar{v}^2 / 2g \quad \ldots (4)$$

where

$\bar{v}$ is the local mean velocity in the approach channel at the cross-section where the head is measured;

α is a coefficient (the kinetic energy or Coriolis coefficient) which takes account of the fact that the kinetic energy head exceeds $\bar{v}^2/2g$ if the velocity distribution across the section is regular but not uniform[1]. In applying this equation in this International Standard, α may be taken as unity, with the tolerances given in later clauses and the provisions of 4.2 and annex B borne in mind.

8.1.4 From equations (2), (3) and (4), it may be deduced that

$$\frac{3\sqrt{3}(C_v^{2/3} - 1)^{1/2}}{C_v} = \frac{2 C_D \, b \, h}{A} \quad \ldots (5)$$

where A is the cross-sectional area of the approach channel, below the observed water level, at the gauging section.

Thus C_v may be deduced in terms of $C_D \, b \, h / A$. To avoid the complicated solution of equation (5) in deducing C_v, figure 3 has been prepared to give the relation between C_v and $C_D \, b \, h / A$. The value of C_D can be obtained by using equation (6) or (6a).

8.2 Computation of discharge

8.2.1 There are two common methods of computing discharge from gauged head readings. The first obtains results by successive approximation techniques and utilizes the basic "total head" equations. This method is admirably suited to solutions by computer techniques since the computer provides an efficient way of carrying out the repetitive calculations involved. The second method utilizes relationships which can be derived between gauge and total heads for particular weir and flow geometries. The coefficient of approach velocity, C_v, in the discharge equation is assessed from tables and graphs.

8.2.2 The basic discharge equation is given in 8.1 in terms of both total and gauged head. Equation (2) may be used to evaluate discharge, with the appropriate value of C_v, read from figure 3.

8.2.3 For water at ordinary temperatures, C_D is a function of head, h, the crest length in the direction of flow, the roughness

1) The formulae given in this International Standard have been derived from experiments where the approach channel velocity distribution was fairly uniform and hence α approximates to unity. If a velocity study at the gauging section indicates that $\alpha > 1{,}25$ the station clearly does not meet the provisions of 4.2 and improvements to the approach channel are necessary. Very approximately

$$\alpha = 1 + 3e^2 - 2e^3$$

where $e = \dfrac{v_{max}}{\bar{v}} - 1$

v_{max} being the highest velocity observed at the cross-section where the head is measured.

of the crest, and the ratio h/b. It can be expressed by the equation

$$C_D = \left(1 - \frac{2xL}{b}\right)\left(1 - \frac{xL}{h}\right)^{3/2} \qquad \ldots (6)$$

where

$x = \delta_*/L$ is a factor which allows for the influence of the boundary layer of the crest

where δ_* is the boundary layer displacement thickness;

L is the length of the horizontal section of the crest in the direction of flow.

For most installations with a good surface finish, the value of δ_*/L will in practice lie in the range 0,002 to 0,004. Provided that $4\,000 < L/k < 10^5$ (k is the roughness value) and $Re > 2 \times 10^5$ (Re is the Reynolds number), δ_*/L may be assumed to be equal to 0,003 without introducing appreciable error. Equation (6) then becomes

$$C_D = \left(1 - \frac{0{,}006\,L}{b}\right)\left(1 - \frac{0{,}003\,L}{h}\right)^{3/2} \qquad \ldots (6a)$$

An example illustrating a more accurate method of calculating C_D on the basis of the boundary layer displacement thickness concept is shown in annex C.

C_D values are valid for both closed front faces (fixed crest) and open front faces (movable crest).

8.3 Limits of application

8.3.1 The practical lower limit of h is related to the magnitude of the influence of fluid properties and boundary roughness. The recommended lower limit is 0,06 m or 0,01 L, whichever is the greater.

8.3.2 The limitations on H/p arise from difficulties experienced when the Froude number in the approach channel exceeds 0,5, coupled with inadequate experimental confirmation at high values of H/p. The recommended upper limit is $H/p = 1{,}5$.

8.3.3 H/L shall not exceed 0,57 and this limitation on H/L arises from the necessity to ensure parallel flow at the critical section on the crest.

8.3.4 The height, p, of the weir shall not be less than 0,15 m. The crest width, b, shall not be less than 0,3 m nor less than H_{max}, nor less than $L/5$.

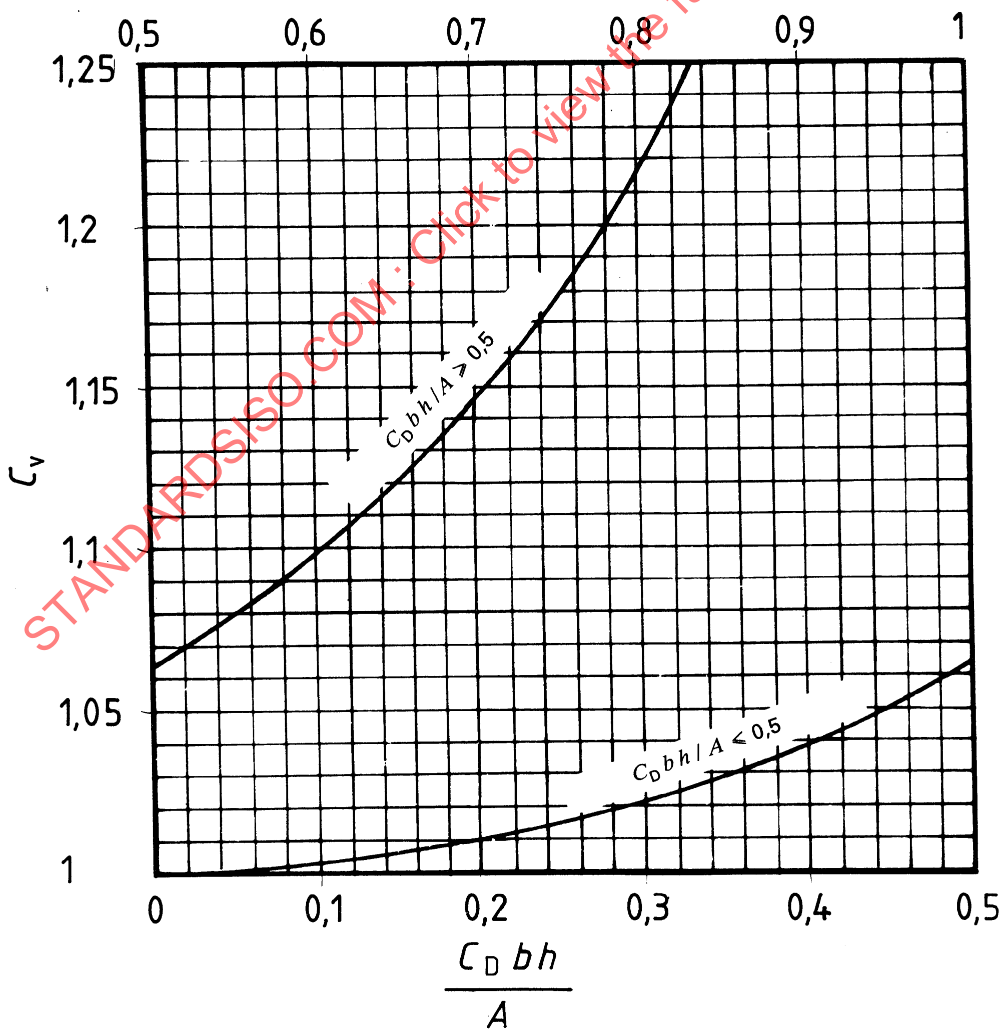

Figure 3 — Coefficient of approach velocity, C_v

8.4 Accuracy

8.4.1 The relative accuracy of flow measurements made with round-nose horizontal broad-crested weirs depends on the accuracy of the head measurement and the measurements of the dimensions of the weir, and the accuracy of the coefficient of discharge as it applies to the weir in use.

8.4.2 With reasonable care and skill in the construction and installation of these weirs, the systematic error (in per cent) in the coefficient of discharge may be deduced from the equation

$$X''_C = \pm \left(2 + 0{,}15\,\frac{L}{H}\right)$$

The random error associated with the determination of the coefficient of discharge may be taken as $X'_C = \pm 1$ % in this case.

The approach velocity coefficient, C_v, is subject to changes in the cross-section of the head gauging section. In the case of regular maintenance of the approach channel, the inaccuracy in C_v is negligible.

8.4.3 The method by which the errors in the coefficient of discharge shall be combined with other sources of error is given in clause 9.

9 Uncertainties in flow measurement

The clause is intended to provide sufficient information for the user of this International Standard to estimate the uncertainty in a measurement of discharge.

9.1 General

9.1.1 Reference should be made to ISO 5168.

9.1.2 The total uncertainty in any flow measurement can be estimated if the uncertainties from various sources are combined. In general, these contributions to the total uncertainty may be assessed and will indicate whether the discharge can be measured with sufficient accuracy for the purpose in hand.

9.1.3 The error may be defined as the difference between the actual rate of flow and that calculated in accordance with the equation for the weir, which is assumed to be constructed and installed in accordance with this International Standard.

The term "uncertainty" will be used to denote the deviation from the true rate of flow within which the measurement is expected to lie some 19 times out of 20 (for 95 % confidence limits).

9.2 Sources of error

9.2.1 The sources of error in the discharge measurement may be identified by considering the discharge equation

$$Q = \left(\frac{2}{3}\right)^{3/2} C_D\, C_v\, b\, \sqrt{g}\, h^{3/2}$$

where

$\left(\frac{2}{3}\right)^{3/2}$ is a numerical constant not subject to error;

g is the acceleration due to gravity (this varies from place to place but, in general, the variation is small enough to be neglected in flow measurements);

C_v is the velocity of approach coefficient of which the error can be neglected (see 8.4).

9.2.2 The only sources of error which need to be considered further are

a) the discharge coefficient, C_D (estimates of the uncertainty in C_D are given in 8.4);

b) the dimensional measurements of the structure, e.g. the width b of the weir;

c) the measured head, h.

9.2.3 The uncertainties in b and h have to be estimated by the user. The uncertainty in their dimensions will depend on the accuracy to which the device as constructed can be measured; in practice this uncertainty may prove to be insignificant in comparison with other uncertainties. The uncertainty in the head will depend on the accuracy of the head measuring device, the determination of the gauge zero, and the technique used. This uncertainty may be small if a vernier or micrometer instrument is used, with a zero determination of comparable precision.

9.3 Types of error

9.3.1 Errors may be classified as random or systematic, the former affecting the reproducibility (precision) of measurement and the latter affecting its true accuracy.

9.3.2 The standard deviation, s_y, of a set of n measurements of a quantity y under steady conditions may be estimated using the following equation:

$$s_y = \left[\frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n - 1}\right]$$

where $\bar{y}$ is the arithmetic mean of the n measurements.

The standard deviation of the mean is then given by

$$s_{\bar{y}} = \frac{s_y}{\sqrt{n}}$$

and the uncertainty in the mean is $2\,s_{\bar{y}}$ (at the 95 % confidence level). This uncertainty is the contribution of random errors in any series of experimental measurements to the total uncertainty.

NOTE — The factor of 2 assumes that n is large. For $n = 6$, the factor should be 2,6; $n = 8$ requires a factor of 2,4; $n = 10$ requires a factor of 2,3; $n = 15$ requires a factor of 2,1.

9.3.3 A measurement may also be subject to systematic error; the mean of very many measured values would thus still differ from the true value of the quantity being measured. For example, an error in setting the zero of a water-level gauge to the crest level produces a systematic difference between the true mean of the measured head and the actual value. A repetition of the measurement does not eliminate systematic errors; the actual value can only be determined by an independent measurement which is known to be more accurate.

9.4 Uncertainties in coefficient values

9.4.1 The errors in this category are both random and systematic.

9.4.2 The values of the discharge coefficients, C, quoted in this International Standard are based on an appraisal of experiments, which may be presumed to have been carefully carried out, with sufficient repetition of the readings to ensure adequate precision. However, when measurements are made on other similar installations, systematic discrepancies between coefficients of discharge may well occur, which may be attributed to variations in the surface finish and installation of the device, the approach conditions, the scale effect between model and site structures, etc.

9.4.3 The uncertainties in the discharge coefficients, quoted in 8.4, are calculated on the basis of the deviation of the experimental data (from various sources) from the theoretical equations given. The suggested uncertainty values thus represent the accumulation of evidence and experience available.

9.5 Uncertainties in measurements made by the user

9.5.1 Both random and systematic errors will occur in measurements made by the user.

9.5.2 Since neither the methods of measurement nor the way in which they are to be made is specified, no numerical values for uncertainties in this category can be given; they shall be estimated by the user. For example, consideration of the method of measurement of the width of the weir should permit the user to determine the uncertainty in this quantity.

9.5.3 The uncertainty in the value of the gauged head shall be determined from an assessment of the separate sources of uncertainty, e.g. the uncertainties in the zero setting, the prevailing wind characteristics, the gauge sensitivity and the backlash in the indicating equipment (where appropriate), and the residual uncertainty in the mean of a series of measurements (where appropriate).

9.6 Combination of uncertainties

9.6.1 The total systematic or random uncertainty is the resultant of several contributory uncertainties, which may themselves be composite uncertainties. Provided that the contributing uncertainties are independent, small and numerous, they may be combined together to give an overall random (or systematic) uncertainty at the 95 % confidence level.

9.6.2 All sources contributing uncertainties will have both random and systematic components. However, in some cases either the random or the systematic component may be predominant and the other component can be neglected by comparison.

9.6.3 Because of the different nature of random and systematic uncertainties, they should not normally be combined with each other. However, with the proviso of 9.6.1, random uncertainties from different sources may be combined together by the root-sum-of-squares rule; systematic uncertainties from different sources may be similarly combined.

9.6.4 The percentage random uncertainty, X'_Q, in the rate of flow may be calculated from the following equation:

$$X'_Q = \pm \sqrt{X'^2_C + X'^2_b + 1{,}5^2 X'^2_h}$$

where

X'_C is the percentage random uncertainty in C_D;

X'_b is the percentage random uncertainty in b;

X'_h is the percentage random uncertainty in h.

In the above

$$X'_b = 100 \frac{e_b}{b}$$

and

$$X'_h = ({}_1X'^2_h + {}_2X'^2_h + \ldots + X'^2_m)^{1/2}$$

where

e_b is the random uncertainty in the breadth measurement;

${}_1X'_h$, ${}_2X'_h$, ... are percentage random uncertainties in the head measurement (see 9.5.3);

X'_m is the percentage random uncertainty in the mean if a series of readings of head measurement are taken at constant water level.

The term X'_m is easily estimated if, for example, a point gauge is used for water level measurement. For continuous or digital recording equipment, the random uncertainty in reading a given water level can be assessed by using laboratory tests on that equipment.

9.6.5 The percentage systematic uncertainty, X''_Q, in the rate of flow may be calculated from the following equation:

$$X''_Q = \pm \sqrt{X''^2_C + X''^2_b + 1{,}5^2 X''^2_h}$$

where

X''_C is the percentage systematic uncertainty in C_D;

X''_b is the percentage systematic uncertainty in b;

X''_h is the percentage systematic uncertainty in h.

In the above

$$X''_h = ({}_1X''^2_h + {}_2X''^2_h + \dots)^{1/2}$$

where ${}_1X''_h$, ${}_2X''_h$, ... are percentage systematic uncertainties in the head measurement (see 9.5.3).

9.7 Presentation of results

Although it is desirable, and frequently necessary, to list the total random and total systematic uncertainties separately, it is appreciated that a simpler presentation of results may be required. For this purpose, random and systematic uncertainties may be combined as shown in ISO 5168:

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

10 Example

The following is an example of the computation of the discharge and the associated uncertainty in a single measurement on a weir having a crest height, p, above the bed of the approach channel of 1 m and operating at a gauged head h = 0,67 m, with a breadth of weir crest b = 10 m and a weir crest length L = 2 m. Ten successive readings of the head gave a standard deviation of the mean $s_{\bar{h}}$ = 1 mm.

10.1 The discharge is calculated using equation (1), given in 8.1.

10.2 The value of the discharge coefficient C_D is determined from equation (6a) as follows:

$$C_D = \left(1 - \frac{0{,}006\,L}{b}\right)\left(1 - \frac{0{,}003\,L}{h}\right)^{3/2}$$

$$= \left(1 - \frac{0{,}006 \times 2}{10}\right)\left(1 - \frac{0{,}003 \times 2}{0{,}67}\right)^{3/2}$$

$$= 0{,}985\,3$$

The approach velocity coefficient is determined using figure 3:

$$C_D\,bh/A = 0{,}985\,3 \times 10 \times 0{,}67/(10 \times 1{,}67) = 0{,}395$$

which gives C_v = 1,038.

Using equation (2)

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g}\, C_D\, C_v\, b\, h^{3/2}$$

$$= 1{,}705 \times 0{,}985\,3 \times 1{,}038 \times 10 \times 0{,}67^{3/2}$$

$$= 9{,}56\ m^3/s$$

10.3 To calculate the uncertainty in this value of Q the uncertainties (in per cent) in the discharge coefficient value are first determined as follows:

$$X'_C = \pm 1\ \%\ \text{(from 8.4)}$$

$$X''_C = \pm \left(2 + 0{,}15\,\frac{L}{h}\right)\ \text{(from 8.4)}$$

$$= \pm \left(2 + 0{,}15 \times \frac{2}{0{,}67}\right)$$

$$= \pm 2{,}45\ \%$$

10.4 If it is assumed that several measurements of the width are taken, the random component of uncertainty in the width measurement can be considered to be negligible. The systematic uncertainty in the width measurement is assumed in this case to be 0,01 m.

Accordingly,

$$X'_b = 0$$

$$X''_b = \pm \frac{0{,}01}{10} \times 100 = \pm 0{,}10\ \%$$

10.5 The magnitude of the uncertainty associated with the head measuring device depends on the particular equipment used. It has been demonstrated that the gauge zero of a digital punched tape recorder can be set to an accuracy of ± 3 mm. This is a systematic uncertainty. There is no random uncertainty associated with the zero setting error because, until the zero is reset, the true zero will have the same magnitude and sign.

Therefore,

$${}_1X'_h = 0$$

$${}_1X''_h = \pm \frac{0{,}003}{0{,}67} \times 100 = \pm 0{,}45\ \%$$

10.6 Uncertainties associated with different types of water level observation equipment can be determined using careful tests under controlled conditions. The random component of uncertainty can be determined by taking a series of readings at a given water level; however, to distinguish this uncertainty from other sources of uncertainty it is necessary that these tests be carried out with the water level always rising (or falling). For the equipment used in this example, the random component of uncertainty in water level measurement is approximately ± 1 mm. Systematic uncertainties in water level measurement occur owing to backlash, tape stretching, etc. Where possible, corrections should be applied, but controlled tests for given types of equipment will indicate the magnitude of the residual systematic uncertainty. In this case, when a digital punched tape recorder is used, this value is approximately ± 2,5 mm.

Accordingly

$$_2X'_h = \frac{0,001}{0,67} \times 100 = 0,15\ \%$$

$$_2X''_h = \frac{0,002\ 5}{0,67} \times 100 = \pm\ 0,37\ \%$$

10.7 The combination of individual uncertainties to obtain the overall uncertainty in discharge can be carried out as follows.

If it is assumed that X'_m is negligible, the uncertainties in water level measurement are

$$X'_h = \pm\ ({_1X'_h}^2 + {_2X'_h}^2)^{1/2} = \pm\ (0 + 0,15^2)^{1/2}$$

$$= \pm\ 0,15\ \%$$

$$X''_h = \pm\ ({_1X''_h}^2 + {_2X''_h}^2)^{1/2} = \pm\ (0,45^2 + 0,37^2)^{1/2}$$

$$= \pm\ 0,58\ \%$$

The total random uncertainty in the discharge measurement is

$$X'_Q = \pm\ (X'^2_C + X'^2_b + 1,5^2\ X'^2_h)^{1/2}$$

$$= \pm\ (1^2 + 0 + 2,25 \times 0,15^2)^{1/2}$$

$$= \pm\ 1,02\ \%$$

The total systematic uncertainty in the discharge measurement is

$$X''_Q = \pm\ (X''^2_C + X''^2_b + 1,5^2\ X''^2_h)^{1/2}$$

$$= \pm\ (2,45^2 + 0,1^2 + 2,25 \times 0,58^2)^{1/2}$$

$$= \pm\ 2,60\ \%$$

To facilitate a simple presentation, the random and systematic uncertainties can be combined by the root-sum-of-squares rule as follows:

$$X_Q = \pm\ (X'^2_Q + X''^2_Q)^{1/2}$$

$$= \pm\ (1,02^2 + 2,60^2)^{1/2}$$

$$= \pm\ 2,79\ \%$$

The flow rate, Q, is therefore 9,56 m^3/s ± 2,8 %. The random uncertainty is ± 1,02 %.

Annex A
(normative)

Symbols and units

Measurements are given in metres and seconds or derivatives of these.

Symbol	Quantity represented	Units of measurement
A	Area of wet cross-section of approach channel $[A = b(h + p)]$	m^2
b	Width of weir crest	m
C_D	Coefficient of discharge	non-dimensional
C_v	Coefficient of approach velocity	non-dimensional
d	Depth of flow	m
e_b	Random uncertainty in width measurement	m
g	Gravitational acceleration	m/s^2
H	Total head $\left[H = h + \frac{\bar{v}^2}{2g}\right]$	m
H_{max}	Maximum value of total head $\left[H_{max} = h_{max} + \frac{\bar{v}^2_{max}}{2g}\right]$	m
h	Measured head of water above weir crest	m
h_{max}	Maximum measured head of water above weir crest	m
k	Roughness	m
L	Length of crest in direction of flow	m
n	Number of measurements	non-dimensional
p	Height of weir crest above upstream bed level	m
p_d	Height of weir crest above downstream bed level	m
Q	Total discharge	m^3/s
R	Radius of the curve of the vertical wall	m
Re	Reynolds number $\left[Re = \frac{vL}{\nu}\right]$	non-dimensional
r	Radius of the edge of the upstream crest	m
s_y	Standard deviation	—
$s_{\bar{y}}$	Standard deviation of the mean	—
X_Q	Overall percentage uncertainty	%
X_b	Percentage uncertainty in b	%
X_C	Percentage uncertainty in C_D	%
X_h	Percentage uncertainty in h	%
x	Boundary layer effect factor	non-dimensional
v_{max}	Highest point velocity observed at the cross-section where the head is measured	m/s
$\bar{v}$	Mean velocity in approach channel	m/s
$\bar{v}_{max}$	Maximum mean velocity in approach channel at maximum rate of flow	m/s
α	Coefficient taking into account non-uniformity of velocity distribution	non-dimensional
δ_*	Boundary layer displacement thickness	m
ε_b	Uncertainty in width measurement	m
ν	Kinematic viscosity	m^2/s

Annex B
(normative)

Velocity distribution

B.1 An even distribution of velocity over the cross-section of the approach channel in the region of the gauging station is necessary for high accuracy of measurement of discharge by means of weirs, notches and flumes. This is because the recommended coefficients are empirical values obtained by various investigators and were usually obtained under ideal laboratory conditions. These laboratory investigations involved the use of either screens to ensure an approximately uniform velocity over the cross-section, or a long straight approach channel conductive to the establishment of a normal distribution of velocities.

B.2 Normal velocity distribution is defined as the distribution of velocities attained in a channel over a long uniform straight reach. A characteristic feature of flow in such a channel is that the velocity is a maximum at about 0,6 times the depth above invert, with the average velocity occurring at about 0,4 times the depth above invert.

B.3 Any deviation from the ideal conditions of either a very uniform velocity or a normal velocity distribution may lead to errors in flow measurement, but quantitative information on the influence of velocity distribution is inadequate to define the acceptable limits of departure from the ideal distributions. With the uncertainties in discharge coefficients quoted in 8.4 in mind, figure B.1 provides some guidance to the type of velocity distribution and evenness thereof that are acceptable in practice.

B.4 In figure B.1, different patterns of isovels are shown. These isovels are contours of equal velocity in the direction of flow.

B.5 The isovels plotted in figures B.1 d), e) and f) provide examples of observed normal velocity distributions, which are clearly acceptable. Figure B.1 a) shows some skewness, but nevertheless approximates to a normal distribution. Figures B.1 b) and c) show appreciable departure from uniformity, and are considered to be representative of the maximum acceptable departure from ideal approach conditions for the uncertainties given.

B.6 If approach conditions are unfavourable, strong secondary currents (spiral flow) may occur. Even though an isovel diagram showing longitudinal components may appear reasonable in such circumstances, the presence of significant cross-components of velocity would make such an installation unacceptable.