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Hydrometry — Open channel flow measurement using thin-plate weirs

Hydrométrie — Mesure de débit dans les canaux découverts au moyen de déversoirs à paroi mince

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 1438 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 2, *Flow measurement structures*.

This second edition cancels and replaces the first edition (ISO 1438-1:1980), of which it constitutes a technical revision. It also incorporates the Amendment ISO 1438-1:1980/Amd 1:1988.

Hydrometry — Open channel flow measurement using thin-plate weirs

1 Scope

This International Standard defines the requirements for the use of rectangular and triangular (V-notch) thin-plate weirs for the measurement of flow of clear water in open channels under free flow conditions. It includes the requirements for the use of full-width rectangular thin-plate weirs in submerged (drowned) flow conditions.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Symbols and abbreviated terms

A	m^2	area of approach channel
B	m	width of approach channel
b	m	measured width of the notch
b_{max}	m	width of notch at maximum head (V-notch)
C		discharge coefficient (gauged head)
C_d		coefficient of discharge
f		drowned flow reduction factor
fC		combined coefficient of discharge
C_v		coefficient of velocity
e_b	m	random uncertainty in the width measurement
g	m/s^2	acceleration due to gravity
H	m	total head above crest level
h	m	upstream gauged head above crest level (upstream head is inferred if no subscript is used)
J		numerical constant
l	m	distance of the head measurement section upstream of the weir
n		number of measurements in a set
p	m	height of the crest relative to the floor
Q	m^3/s	volumetric rate of flow
S		submergence ratio, h_2/h_1

S_1		modular limit
$\overline{V}$	m/s	mean velocity
U	%	expanded percentage uncertainty
$u^*(b)$	%	percentage uncertainty in b
$u^*(C)$	%	percentage uncertainty in C
$u^*(E)$	%	percentage uncertainty in datum measurement
$u^*(h_1)$	%	percentage uncertainty in h_1
$u^*(Q)$	%	percentage uncertainty in Q
α	°	notch angle

Subscripts:

1 upstream
2 downstream
e effective
r rectangular
t triangular

5 Principle

The discharge over thin-plate weirs is a function of the upstream head on the weir (for free-flow), upstream and downstream head (for drowned flow), the size and shape of the discharge area and an experimentally determined coefficient which takes into account the head, the geometrical properties of the weir and approach channel and the dynamic properties of the water.

6 Installation

6.1 General

General requirements of weir installations are described in the following clauses. Special requirements of different types of weirs are described in clauses which deal with specific weirs (see Clauses 9 and 10).

6.2 Selection of site

The type of weir to be used for discharge measurement is determined in part by the nature of the proposed measuring site. Under some conditions of design and use, weirs shall be located in rectangular flumes or in weir boxes which simulate flow conditions in rectangular flumes. Under other conditions, weirs may be located in natural channels as well as flumes or weir boxes, with no significant difference in measurement accuracy. Specific site-related requirements of the installation are described in 6.3.

6.3 Installation conditions

6.3.1 General

Weir discharge is critically influenced by the physical characteristics of the weir and the weir channel. Thin-plate weirs are especially dependent on installation features which control the velocity distribution in the approach channel and on the construction and maintenance of the weir crest in meticulous conformance with standard specifications.

6.3.2 Weir

Thin-plate weirs shall be vertical and perpendicular to the walls of the channel. The intersection of the weir plate with the walls and floor of the channel shall be watertight and firm, and the weir shall be capable of withstanding the maximum flow without distortion or damage.

Stated practical limits associated with different discharge formulae such as minimum width, minimum weir height, minimum head, and maximum values of h/p and b/B (where h is the measured head, p is the height of crest relative to floor, b is the measured width of the notch and B is the width of the approach channel), are factors which influence both the selection of weir type and the installation.

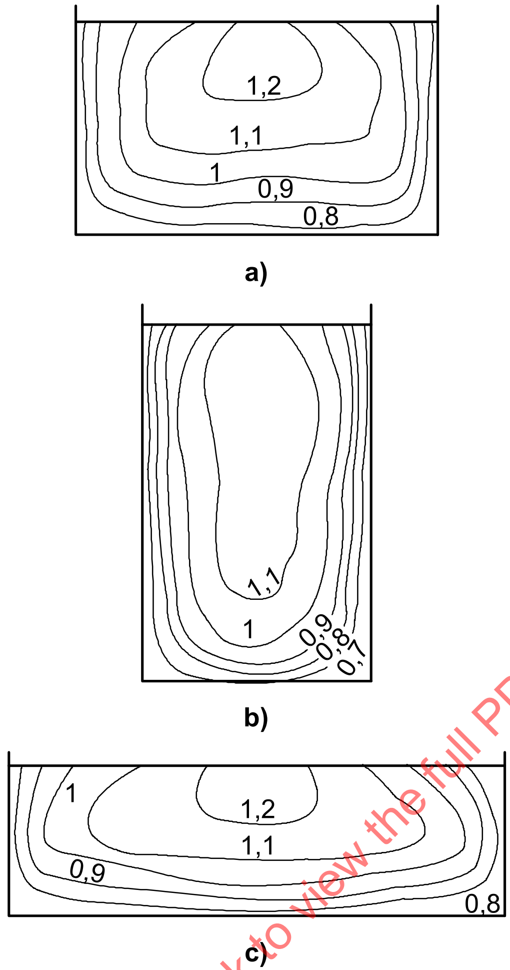
6.3.3 Approach channel

For the purposes of this International Standard, the approach channel is the portion of the weir channel which extends upstream from the weir a distance not less than 5 times the width of the nappe at maximum head. If the weir is located in a weir tank, ideally the length of the tank should equal to 10 times the width of the nappe at maximum head. Information on the use of small weir tanks is given in Annex A.

The flow in the approach channel shall be uniform and steady, with the velocity distribution approximating that in a channel of sufficient length to develop satisfactory flow in smooth, straight channels. Figure 1 shows measured velocity distributions perpendicular to the direction of flow in rectangular channels, upstream from the influence of a weir. Baffles and flow straighteners can be used to simulate satisfactory velocity distribution, but their location with respect to the weir shall be not less than the minimum length prescribed for the approach channel.

The influence of approach-channel velocity distribution on weir flow increases as h/p and b/B increase in magnitude. If a weir installation unavoidably results in a velocity distribution that is appreciably non-uniform, the possibility of error in calculated discharge should be checked by means of an alternative discharge-measuring method for a representative range of discharges.

If the approach conditions are judged to be unsatisfactory, then flow straighteners shall be introduced in accordance with Annex B.



NOTE The contours refer to values of local flow velocity relative to the mean cross-sectional velocity.

Figure 1 — Examples of normal velocity distribution in rectangular channels

6.3.4 Downstream channel

For most applications, the level of the water in the downstream channel shall be a sufficient vertical distance below the crest to ensure free, fully ventilated discharges. Free (non-submerged) discharge occurs when the discharge is independent of the downstream water level. Fully ventilated discharge is ensured when the air pressure on the lower surface of the nappe is fully ventilated. Drowned flow operation is permitted for full width weirs under certain conditions (see 9.7.2). Under these circumstances, downstream water levels may rise above crest level.

7 Measurement of head

7.1 Head measuring devices

In order to obtain the discharge measurement accuracies specified for the standard weirs, the head on the weir shall be measured with a laboratory-grade hook gauge, point gauge, manometer, or other gauge of equivalent accuracy. For a continuous record of head variants, precise float gauges and servo-operated point gauges can be used. Staff and tape gauges can be used when less accurate measurements are acceptable.

Additional specifications for head-measuring devices are given in ISO 4373 [1].

7.2 Stilling or float well

For the exceptional case where surface velocities and disturbances in the approach channel are negligible, the headwater level can be measured directly (for example, by means of a point gauge mounted over the water surface). Generally, however, to avoid water-level variations caused by waves, turbulence or vibration, the headwater level should be measured in a separate stilling well.

Separate stilling wells are connected to the approach channel by means of a suitable conduit, equipped if necessary with a throttle valve to damp oscillations. At the channel end of the conduit, the connection is made to floor or wall piezometers or a static tube at the head-measurement section.

Additional specifications for stilling wells are given in ISO 1100-1 [2].

7.3 Head-measurement section

7.3.1 Upstream head-measurement

The head-measurement section shall be located a sufficient distance upstream from the weir to avoid the region of surface drawdown caused by the formation of the nappe. On the other hand, it shall be sufficiently close to the weir that the energy loss between the head-measurement section and the weir is negligible. For the weirs included in this International Standard, the location of the head-measurement section will be satisfactory if it is at a distance equal to 2 to 4 times the maximum head ($2h_{max}$ to $4h_{max}$) upstream from the weir.

If high velocities occur in the approach channel or if water-surface disturbances or irregularities occur at the head-measurement section because of high values of h/p or b/B, it may be necessary to install several pressure intakes to ensure that the head measured in the gauge well is representative of the average head across the measurement section.

In the case of a full-width thin-plate weir, the effect of frictional effects upon the upstream channel requires an adjustment to the standard coefficient of discharge. The correction is in terms of both l/h and h/p and given in Table 1.

Table 1 — Factors to be applied to the standard discharge coefficient values

h/p	l/h			
	2	4	6	8
3,5 to 4,0	1,00	1,00	0,96	0,92
3,0 to 3,5	1,00	1,00	0,97	0,94
2,5 to 3,0	1,00	1,00	0,98	0,96
2,0 to 2,5	1,00	1,00	0,99	0,98
Less than 2,0	1,00	1,00	1,00	1,00

7.3.2 Downstream head measurement

If the weir is to be operated in the submerged (drowned) flow range, a measurement of downstream head is required in addition to that upstream. The downstream head measurement position shall be 10 h_{max} downstream from the upstream face of the weir. If a stilling well is included in the design, it is recommended that the downstream head measurement be located no closer to the weir than 4 h_{max}.

7.4 Head-gauge datum (gauge zero)

Accuracy of head measurements is critically dependent upon the determination of the head-gauge datum or gauge zero, which is defined as the gauge reading corresponding to the level of the weir crest (rectangular weirs) or the level of the vertex of the notch (triangular-notch weirs). When necessary, the gauge zero shall be checked. Numerous acceptable methods of determining the gauge zero are in use. Typical methods are described in subsequent clauses dealing specifically with rectangular and triangular weirs. (See Clauses 9 and 10.)

Because of surface tension, the gauge zero cannot be determined with sufficient accuracy by reading the head gauge with the water in the approach channel drawn down to the apparent crest (or notch) level.

8 Maintenance

Maintenance of the weir and the weir channel is necessary to ensure accurate measurements.

The approach channel shall be kept free of silt, vegetation and obstructions which might have deleterious effects on the flow conditions specified for the standard installation. The downstream channel shall be kept free of obstructions which might cause submergence or inhibit full ventilation of the nappe under all conditions of flow.

The weir plate shall be kept clean and firmly secured. In the process of cleaning, care shall be taken to avoid damage to the crest or notch, particularly the upstream edges and surfaces. Construction specifications for these most sensitive features should be reviewed before maintenance is undertaken.

Head-measurement piezometers, connecting conduits and the stilling well shall be cleaned and checked for leakage. The hook or point gauge, manometer, float or other instrument used to measure the head shall be checked periodically to ensure accuracy.

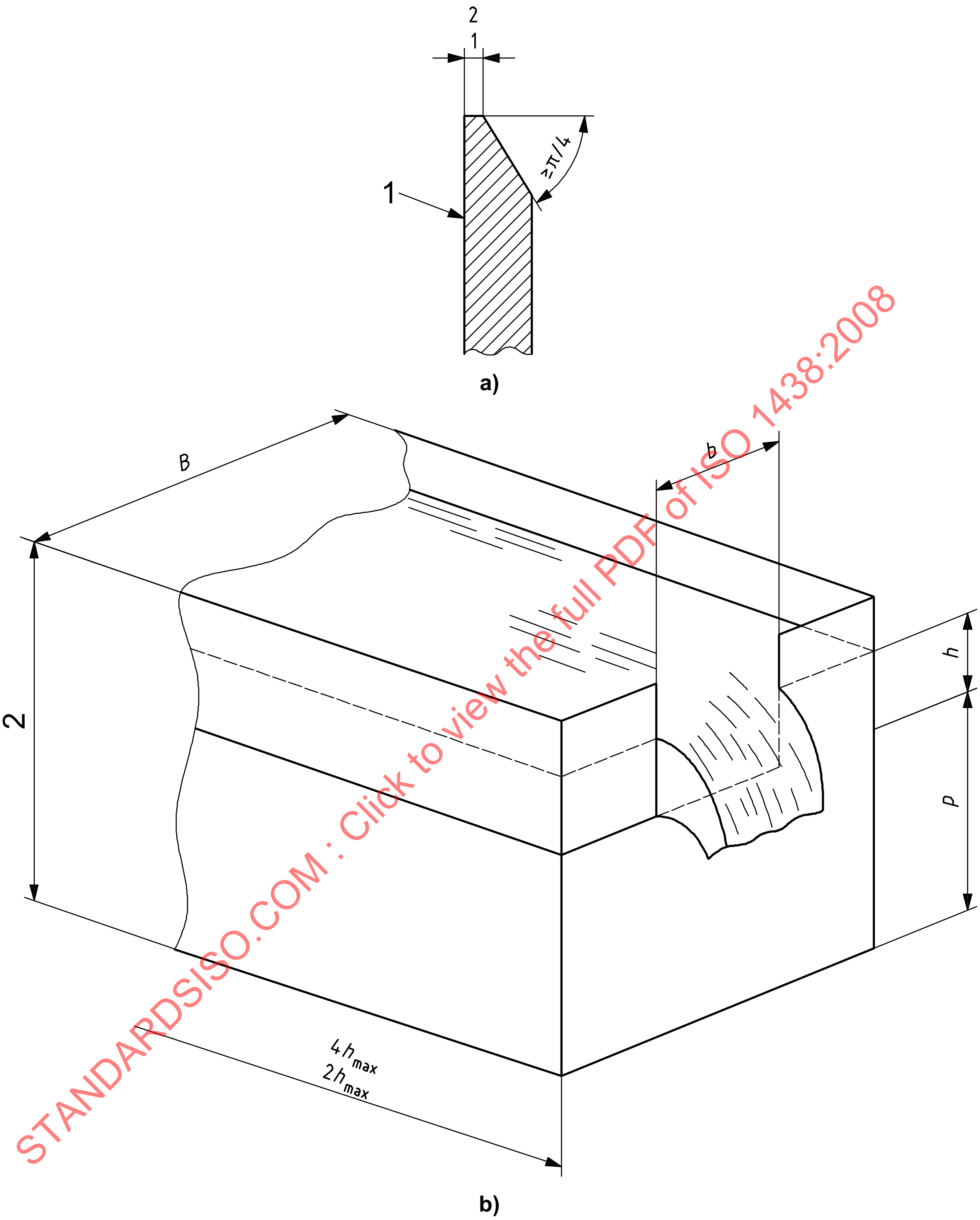
If a flow straightener is used in the approach channel, perforated plates shall be kept clean so that the percentage open area remains greater than 40 %.

9 Rectangular thin-plate weir

9.1 Types

The rectangular thin-plate weir is a general classification in which the rectangular-notch weir is the basic form and the full-width weir is a limiting case. A diagrammatic illustration of the basic weir form is shown in Figure 2 with intermediate values of b/B and h/p. When $b/B = 1{,}0$, that is when the width of the weir (b) is equal to the width of the channel at the weir section (B), the weir is of full-width type (also referred to as a “suppressed” weir, because its nappe lacks side contractions).

Dimensions in millimetres



Key

1 upstream face of weir plate

2 head measurement section, h_1

Figure 2 — Rectangular-notch, thin-plate weir

9.2 Specifications for the standard weir

The basic weir form consists of a rectangular notch in a vertical, thin plate. The plate shall be plane and rigid and perpendicular to the walls and the floor of the approach channel. The upstream face of the plate shall be smooth (in the vicinity of the notch it shall be equivalent in surface finish to that of rolled sheet-metal).

The vertical bisector of the notch shall be equidistant from the two walls of the channel. The crest surface of the notch shall be a horizontal, plane surface, which shall form a sharp edge at its intersection with the upstream face of the weir plate. The width of the crest surface, measured perpendicular to the face of the plate, shall be between 1 mm and 2 mm. The side surfaces of the notch shall be vertical, plane surfaces which shall make sharp edges at their intersection with the upstream face of the weir plate. For the limiting case of the full-width weir, the crest of the weir shall extend to the walls of the channel, which in the vicinity of the crest shall be plane and smooth (see also 9.3).

To ensure that the upstream edges of the crest and the sides of the notch are sharp, they shall be machined or filed, perpendicular to the upstream face of the weir plate, free of burrs or scratches and untouched by abrasive cloth or paper. The downstream edges of the notch shall be chamfered if the weir plate is thicker than the maximum allowable width of the notch surface. The surface of the chamfer shall make an angle of not less than $\pi/4$ radians (45°) with the crest and side surfaces of the notch (see detail, Figure 2). The weir plate in the vicinity of the notch preferably shall be made of corrosion-resistant metal; but if it is not, all specified smooth surfaces and sharp edges shall be kept coated with a thin, protective film (for example, oil, wax, silicone) applied with a soft cloth.

9.3 Specifications for installation

The specifications stated in 6.3 shall apply. In general, the weir shall be located in a straight, horizontal, rectangular approach channel if possible. However, if the effective opening of the notch is so small in comparison with the area of the upstream channel that the approach velocity is negligible, the shape of the channel is not significant. In any case, the flow in the approach channel shall be uniform and steady, as specified in 6.3.3.

If the width of the weir is equal to the width of the channel at the weir section (i.e. a full-width weir), the sides of the channel upstream from the plane of the weir shall be vertical, plane, parallel and smooth (equivalent in surface finish to that of rolled sheet-metal). The sides of the channel above the level of the crest of a full-width weir shall extend at least 0,3 h_{max} downstream from the plane of the weir. Fully ventilated discharge shall be ensured as specified in 6.3.4.

The approach channel floor shall be smooth, flat and horizontal when the height of the crest relative to the floor (p) is small and/or h/p is large. For rectangular weirs, the floor should be smooth, flat and horizontal, particularly when p is less than 0,1 m and/or h_{max}/p is greater than 1. Additional conditions are specified in connection with the recommended discharge formulae.

9.4 Determination of gauge zero

The head-gauge datum or gauge zero shall be determined with great care, and it shall be checked when necessary. A typical, acceptable method of determining the gauge zero for rectangular weirs is described as follows.

a) Still water in the approach channel is drawn to a level below the weir crest.

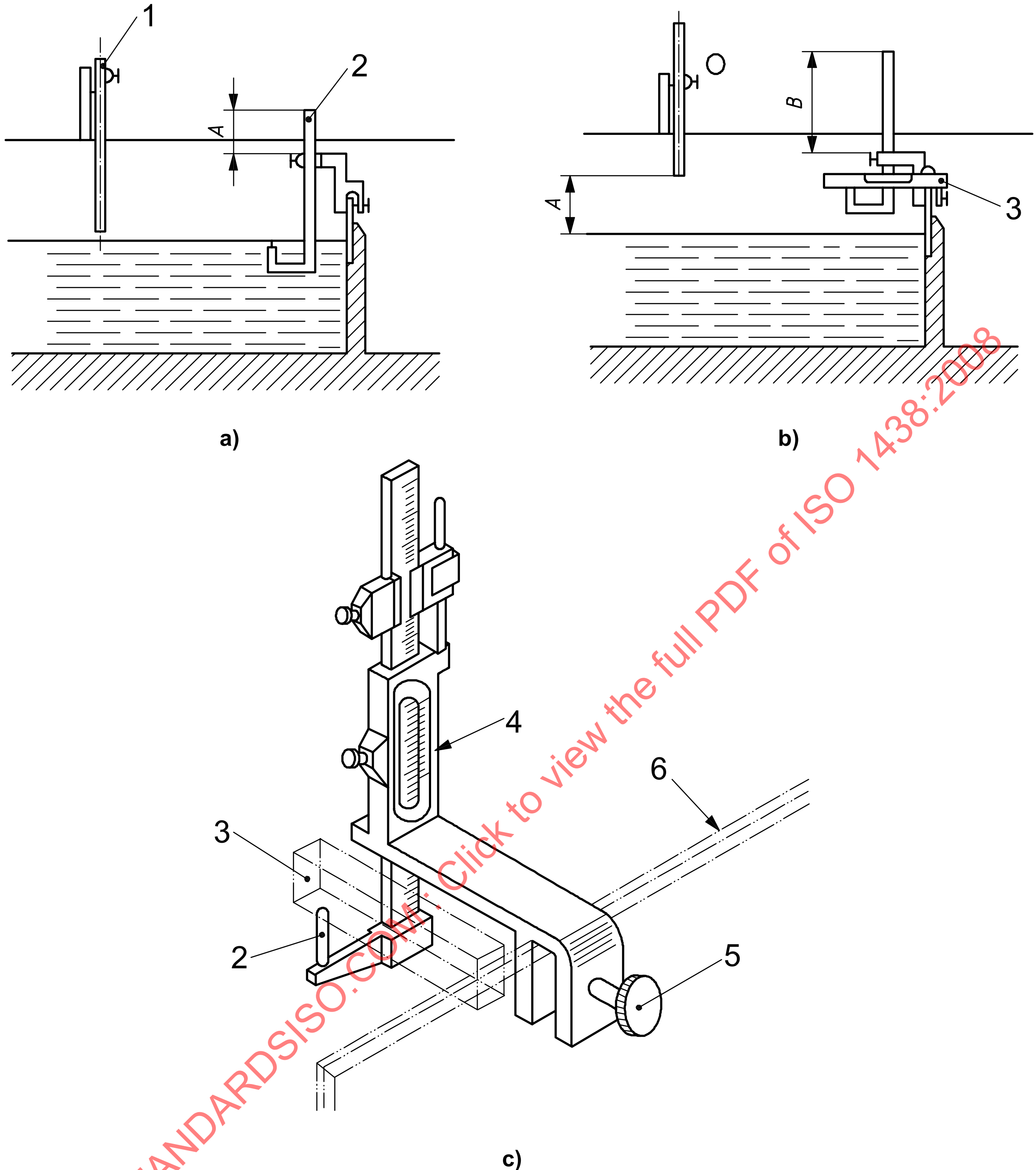
b) A temporary hook gauge is mounted over the approach channel, a short distance upstream from the weir crest.

c) A precise machinists' level is placed with its axis horizontal, with one end lying on the weir crest and the other end on the point of the temporary hook gauge (the gauge having been adjusted to hold the level in this position). The reading of the temporary gauge is recorded.

d) The temporary hook gauge is lowered to the water surface in the approach channel and its reading is recorded. The permanent gauge is adjusted to read the level in the gauge well, and this reading is recorded.

e) The computed difference between the two readings of the temporary gauge is added to the reading of the permanent gauge. The sum is the gauge zero for the permanent gauge.

Figure 3 illustrates the use of this procedure with a form of temporary hook gauge which is conveniently mounted on the weir plate.



Key

1 permanent gauge
2 temporary hook gauge
3 precision level
4 vernier micrometer
5 set screw
6 weir crest

Figure 3 — Determination of gauge zero for rectangular weir

9.5 Discharge formulae — General

Recommended discharge formulae for rectangular thin-plate weirs are presented in three categories:

a) modular discharge equation for the basic weir form (all values of b/B);

b) modular discharge equation for full-width weirs ($b/B = 1{,}0$);

c) non-modular discharge equation for full-width weirs.

9.6 Formulae for the basic weir form (all values of b/B)

9.6.1 Kindsvater-Carter formula

The Kindsvater-Carter formula for the basic weir form is:

$$Q = C_d \frac{2}{3} \sqrt{2g} b_e h_e^{3/2} \quad (1)$$

where

C_d is the coefficient of discharge;

b_e is the effective width;

h_e is the effective head.

9.6.1.1 Evaluation of C_d, k_b and k_h

Figure 4 shows experimentally determined values of C_d as a function of h/p for representative values of b/B. Values of C_d for intermediate values of b/B can be determined by interpolation.

The coefficient of discharge C_d has been determined by experiment as a function of two variables from the formula:

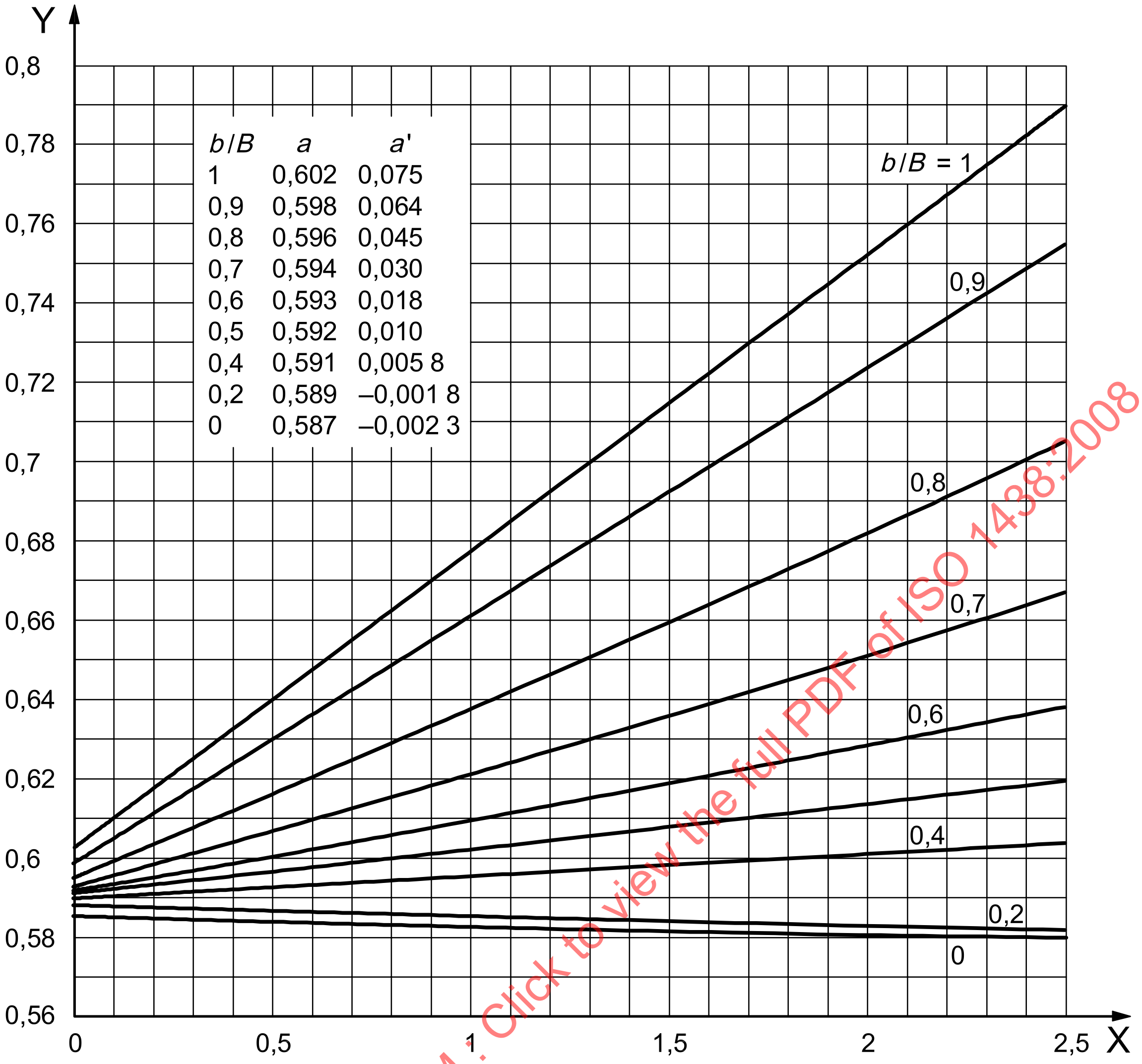
$$C_d = f\left(\frac{b}{B}, \frac{h}{p}\right) \quad (2)$$

The effective width and head are defined by Equations (3) and (4):

$$b_e = b + k_b \quad (3)$$

$$h_e = h + k_h \quad (4)$$

in which k_b and k_h are experimentally determined quantities, in metres, which compensate for the combined effects of viscosity and surface tension.



Key

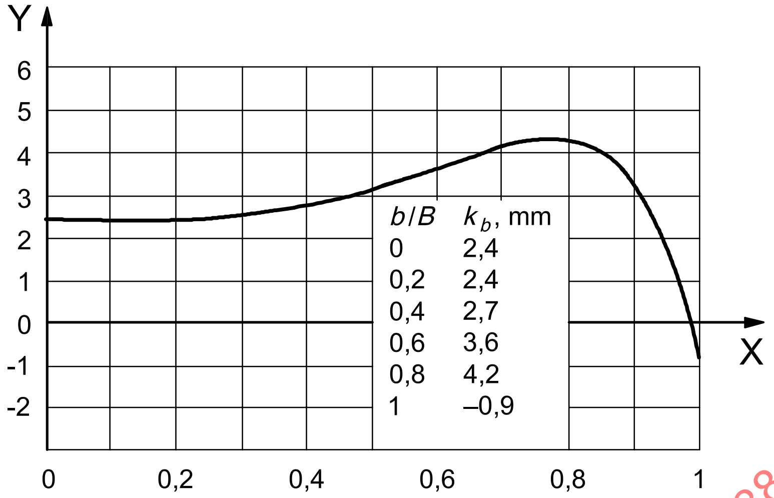
X value of $\frac{h}{p}$

Y value of C_d

Figure 4 — Coefficient of discharge $C_d = a + a'\left(\frac{h}{p}\right)$

Figure 5 shows values of k_b, which have been experimentally determined as a function of b/B.

Experiments have shown that k_h can be taken to have a constant value of 0,001 m for weirs constructed in strict conformance with recommended specifications.



Key

X b/B

Y k_b, in millimetres

Figure 5 — Value of k_b related to b/B

9.6.1.2 Formulae for C_d

For specific values of b/B, the relationship between C_d and h/p has been shown by experiment (see Figure 4) to be of the linear form $C_d = a + a'\left(\frac{h}{p}\right)$.

Thus, for the values of b/B shown on Figure 4, formulae for C_d can be written as follows:

$$\left(\frac{b}{B} = 1{,}0\right): C_d = 0{,}602 + 0{,}075\frac{h}{p} \quad (5)$$

$$\left(\frac{b}{B} = 0{,}9\right): C_d = 0{,}598 + 0{,}064\frac{h}{p} \quad (6)$$

$$\left(\frac{b}{B} = 0{,}8\right): C_d = 0{,}596 + 0{,}045\frac{h}{p} \quad (7)$$

$$\left(\frac{b}{B} = 0{,}7\right): C_d = 0{,}594 + 0{,}030\frac{h}{p} \quad (8)$$

$$\left(\frac{b}{B} = 0{,}6\right): C_d = 0{,}593 + 0{,}018\frac{h}{p} \quad (9)$$

$$\left(\frac{b}{B} = 0{,}5\right): C_d = 0{,}592 + 0{,}010\frac{h}{p} \quad (10)$$

$$\left(\frac{b}{B} = 0{,}4\right): C_d = 0{,}591 + 0{,}005\,8\frac{h}{p} \quad (11)$$

$$\left(\frac{b}{B}=0,2\right): C_\text{d}=0,589+0,0018\frac{h}{p} \tag{12}$$

$$\left(\frac{b}{B}=0\right): C_\text{d}=0,587+0,002\,3\frac{h}{p} \tag{13}$$

For intermediate values of b/B, formulae for C_d can be determined satisfactorily by interpolation.

9.6.1.3 Practical limitations on h/p, h, b and p

Practical limits are placed on h/p because head-measurement difficulties and errors result from surges and waves which occur in the approach channel at larger values of h/p. Limits are placed on h to avoid the “clinging nappe” phenomenon which occurs at very low heads. Limits are placed on b because of uncertainties regarding the combined effects of viscosity and surface tension represented by the quantity of k_b at very small values of b. Limits are placed on p and $B - b$ to avoid the instabilities which result from eddies that form in the corners between the channel boundaries and the weir when values of p and $B - b$ are small.

For conservative practice, limitations applicable to the use of the Kindsvater-Carter formulae are:

a) h/p shall be not greater than 2,5;

b) h shall be not less than 0,03 m;

c) b shall be not less than 0,15 m;

d) p shall be not less than 0,10 m;

e) either $(B - b)/2 = 0$ (full width weir) or $(B - b)/2$ shall not be less than 0,10 m (contracted weir).

9.7 Formulae for full-width weirs ($b/B = 1,0$)

9.7.1 Modular flow discharge equation

The Rehbock formula in the form proposed in 1929 is of the effective-head variety:

$$Q = C_\text{d}\frac{2}{3}\sqrt{2g}\,b\,h_{1\text{e}}^{3/2} \tag{14}$$

in which

$$C_\text{d}=0,602+0,083\frac{h_1}{p} \tag{15}$$

$$h_{1\text{e}}=h_1+0,001\,2 \tag{16}$$

Practical limitations applicable to the use of the Rehbock formula are:

a) h_1/p shall be not greater than 4,0;

b) h_1 shall be between 0,03 and 1,0 m;

c) b shall be not less than 0,30 m;

d) p shall be not less than 0,06 m.

9.7.2 Non-modular flow discharge equation

Submerged (drowned) flow occurs when the tailwater level downstream from a weir affects the flow. The weir operates in the non-modular condition. For this condition, an additional downstream measurement of head (h_2) is required and a drowned flow reduction factor (f) is applied to the modular discharge equation.

Since the modular limit of a full-width thin-plate weir is significantly influenced by the ratio h_1/P, the modular limit increasing with h_1/P, drowned flow performance of the typical full-width thin-plate weir is shown in Figure 6 and defined by the equations below:

For $h_1/p = 0{,}5$, then $f = 1{,}007\,[0{,}975 - (h_2/h_1)^{1{,}45}]^{0{,}265}$ in the range $0{,}00 < h_2/h_1 < 0{,}97$

For $h_1/p = 1{,}0$, then $f = 1{,}026\,[0{,}960 - (h_2/h_1)^{1{,}55}]^{0{,}242}$ in the range $0{,}20 < h_2/h_1 < 0{,}97$

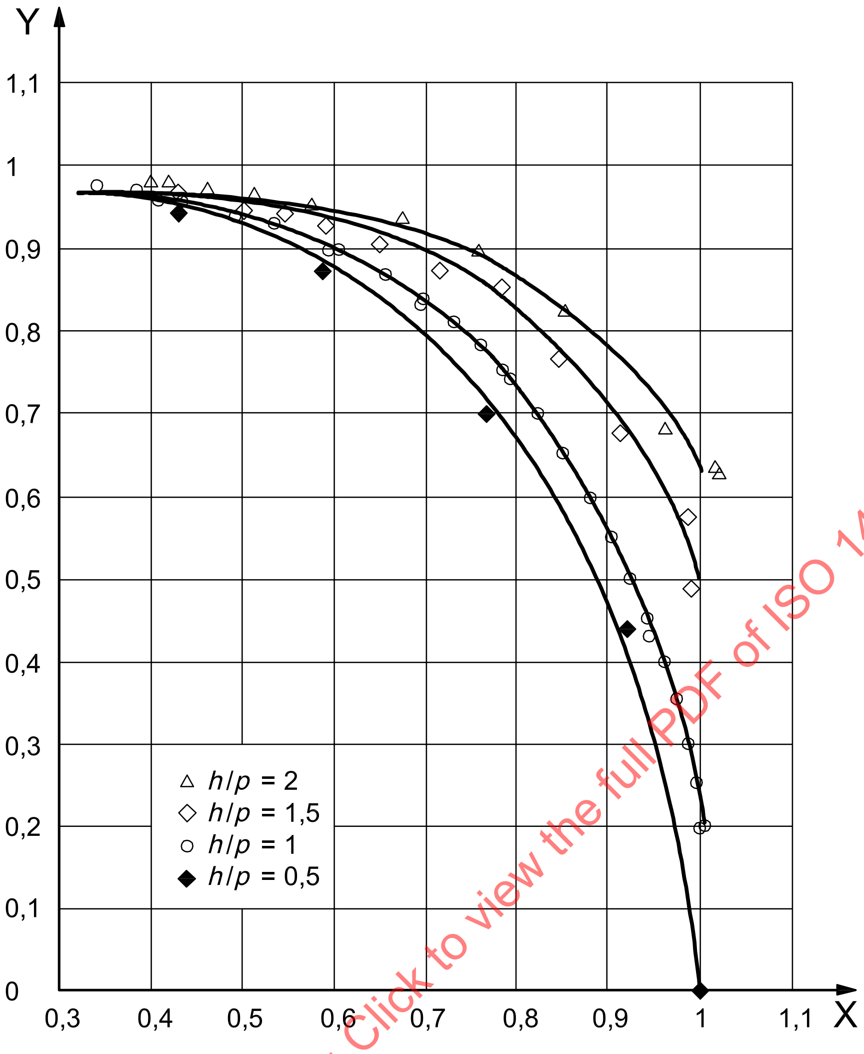
For $h_1/p = 1{,}5$, then $f = 1{,}098\,[0{,}952 - (h_2/h_1)^{1{,}75}]^{0{,}220}$ in the range $0{,}50 < h_2/h_1 < 0{,}97$

For $h_1/p = 2{,}0$, then $f = 1{,}155\,[0{,}950 - (h_2/h_1)^{1{,}85}]^{0{,}219}$ in the range $0{,}63 < h_2/h_1 < 0{,}97$

Thus, the Rehbock formula (1929) for drowned flow becomes:

$$Q = fC_\mathrm{d}\frac{2}{3}\sqrt{2g}\,b\,h_{1\mathrm{e}}^{3/2} \qquad (17)$$

NOTE This adjustment only applies where the upstream and downstream measurements are in the same horizontal plane, i.e. there is no drop in the channel bottom at, or downstream, of the weir.



Key

X value of $\frac{h_2}{h_1}$

Y value of f

Figure 6 — Drowned flow performance of the full-width thin-plate weir

10 Triangular-notch thin-plate weir

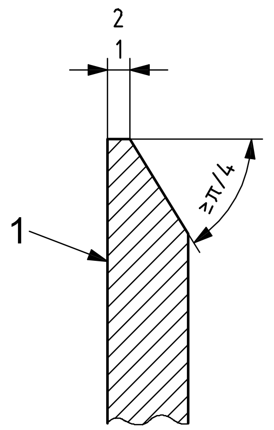
10.1 Specifications for the standard weir

The triangular-notch thin-plate weir consists of a V-shaped notch in a vertical, thin plate. A diagrammatic illustration of the triangular-notch weir is shown in Figure 7. The weir plate shall be plane and rigid and perpendicular to the walls and the floor of the channel. The upstream face of the plate shall be smooth (in the vicinity of the notch, it shall be equivalent in surface finish to that of rolled sheet-metal).

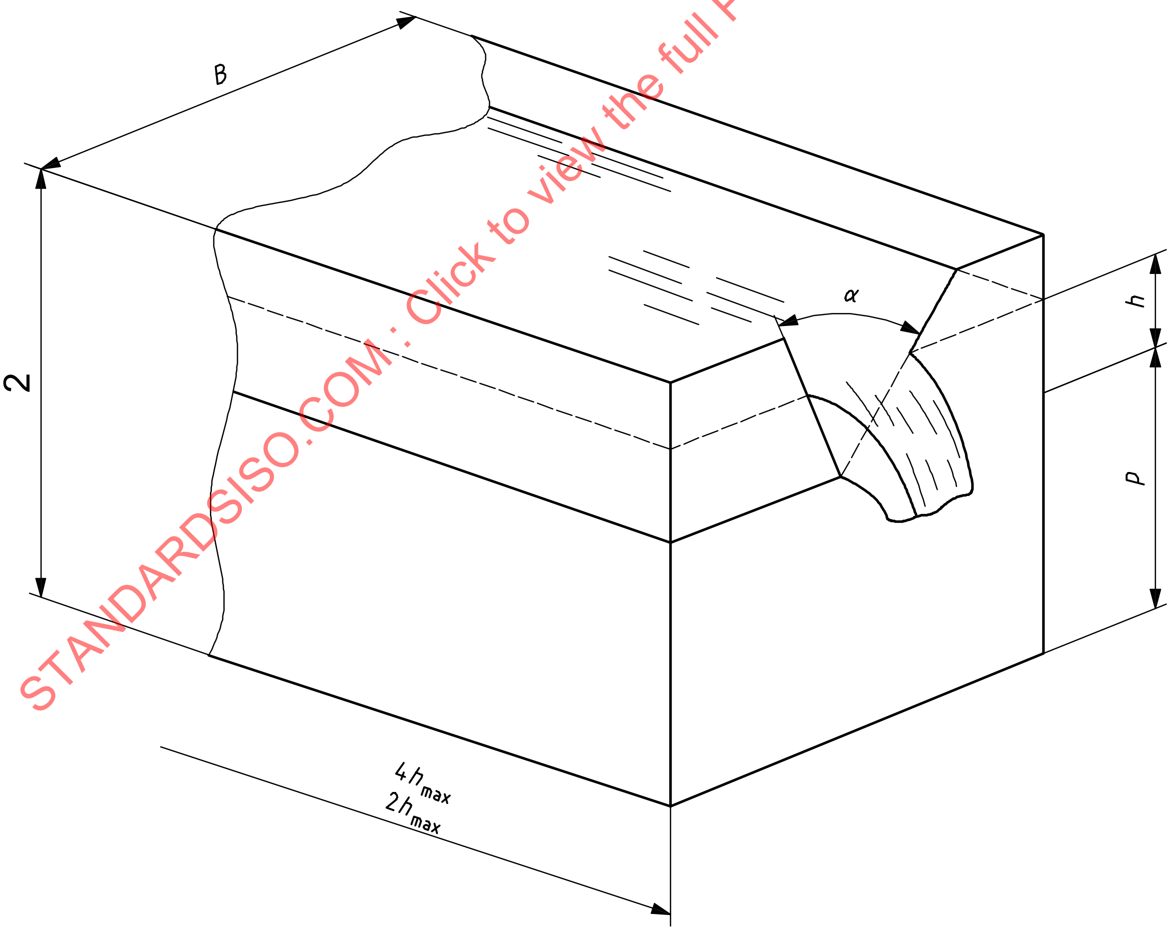
The bisector of the notch shall be vertical and equidistant from the two walls of the channel. The surfaces of the notch shall be plane surfaces, which shall form sharp edges at their intersection with the upstream face of the weir plate. The width of the notch surfaces, measured perpendicular to the face of the plate, shall be between 1 mm and 2 mm.

To ensure that the upstream edges of the notch are sharp, they shall be machined or filed, perpendicular to the upstream face of the plate, free of burrs or scratches and untouched by abrasive cloth or paper. The downstream edges of the notch shall be chamfered if the weir plate is thicker than the maximum allowable width of the notch surface. The surface of the chamfer shall make an angle of not less than π/4 radians (45°) with the surface of the notch (see detail, Figure 7). The weir plate in the vicinity of the notch preferably shall be made of corrosion-resistant metal; but if it is not, all specified smooth surfaces shall be kept coated with a thin protective film (for example, oil, wax, silicone) applied with a soft cloth.

Dimensions in millimetres



a)



b)

Key

1 upstream face of weir plate

2 head measurement section

Figure 7 — Triangular-notch thin-plate weir

10.2 Specifications for the installation

The specifications stated in 6.3 shall apply. In general, the weir shall be located in a straight, horizontal, rectangular channel if possible. However, if the effective opening of the notch is so small in comparison with the area of the upstream channel that the approach velocity is negligible, the shape of the channel is not significant. In any case, the flow in the approach channel shall be uniform and steady, as specified in 6.3.3.

If the top width of the nappe at maximum head is large in comparison with the width of the channel, the channel walls shall be straight, vertical and parallel. If the height of the vertex relative to the level of the floor is small in comparison with the maximum head, the channel floor shall be smooth, flat and horizontal. In general, the approach channel should be smooth, straight and rectangular when B/b_{max} is less than 3 and/or h_{max}/p is greater than 1. Additional conditions are specified in connection with the recommended discharge formulae.

10.3 Specifications for head measurement

10.3.1 General

The conditions specified in 7.1, 7.2 and 7.3 shall apply without exception.

10.3.2 Determination of notch angle

Precise head measurements for triangular-notch weirs require that the notch angle (angle included between sides of the notch) be measured accurately. One of several satisfactory methods is described as follows.

a) Two true disks of different, micrometered diameters are placed in the notch with their edges tangent to the sides of the notch.

b) The vertical distance between the centres (or two corresponding edges) of the two disks is measured with a micrometer caliper.

c) The notch angle α is twice the angle whose sine is equal to the differences between the radii of the disks divided by the distance between the centres of the disks.

10.3.3 Determination of gauge zero

The head-gauge datum or gauge zero shall be determined with great care, and it shall be checked when necessary. A typical acceptable method of determining the gauge zero for triangular notch weirs is described as follows.

a) Still water in the approach channel is drawn to a level below the vertex of the notch.

b) A temporary hook gauge is mounted over the approach channel, with its point a short distance upstream from the vertex of the notch.

c) A true cylinder of known (micrometered) diameter is placed with its axis horizontal, with one end resting in the notch and the other end balanced on the point of the temporary hook gauge. A machinists' level is placed on top of the cylinder, and the hook gauge is adjusted to make the cylinder precisely horizontal. The reading of the temporary gauge is recorded.

d) The temporary hook gauge is lowered to the water surface in the approach channel and the reading is recorded. The permanent gauge is adjusted to read the level in the gauge well, and this reading is recorded.

e) The distance (y) from the top of the cylinder to the vertex of the notch is computed with the known value of the notch angle (α) and the radius (r) of the cylinder $\left[y = \left(r / \sin\frac{\alpha}{2} \right) + r \right]$. This distance is then subtracted from the reading recorded in c), the result being the reading of the temporary gauge at the vertex of the notch.

f) The difference between the computed reading in e) and the reading of the temporary gauge in d) is added to the reading of the permanent gauge in d). The sum is the gauge zero for the permanent gauge.

An advantage of this method is that it refers the gauge zero to the geometrical vertex which is defined by the sides of the notch.

10.4 Discharge formulae — General

Recommended discharge formulae for triangular-notch thin-plate weirs are presented in two categories:

a) formula for all notch angles between $\pi/9$ and $5\pi/9$ radians (20° and 100°);

b) formulae for specific notch angles (fully contracted weirs).

10.5 Formula for all notch angles between $\pi/9$ and 5 $\pi/9$ radians (20° and 100°)

10.5.1 Kindsvater-Shen formula

The Kindsvater-Shen formula for triangular notch weirs is

$$Q = C_{\mathrm{d}} \frac{8}{15} \tan\frac{\alpha}{2} \sqrt{2g}\, h_{\mathrm{e}}^{5/2} \tag{18}$$

where

C_{d} is the coefficient of discharge;

h_{e} is the effective head.

The coefficient of discharge C_{d} has been determined by experiment as a function of three variables (see Figure 8).

$$C_{\mathrm{d}} = f\left(\frac{h}{p}, \frac{p}{B}, \alpha\right) \tag{19}$$

where

p is the height of the vertex of the notch with respect to the floor of the approach channel;

B is the width of the approach channel;

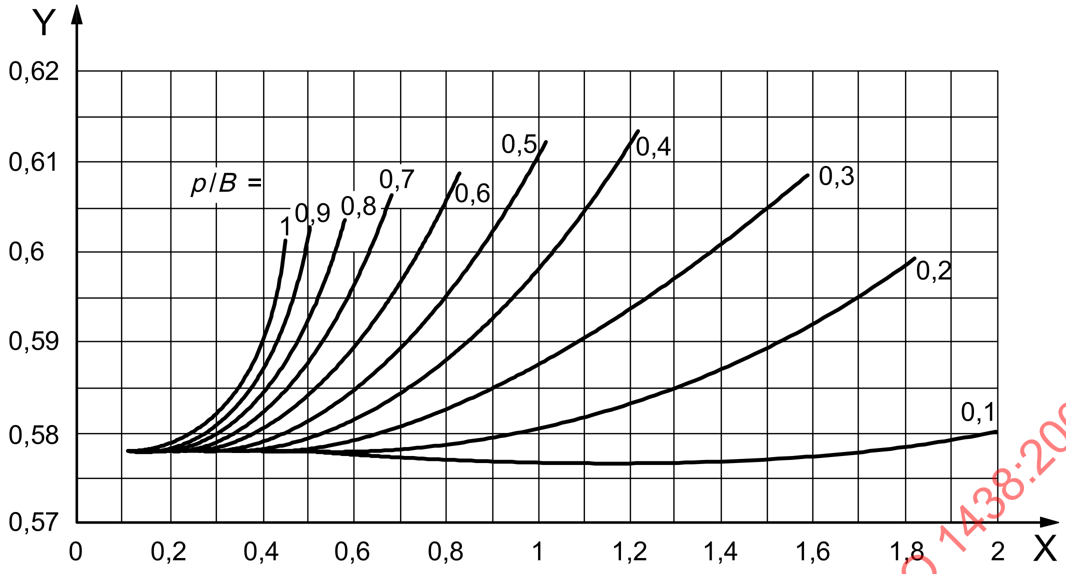
h_{e} is defined by Equation (20):

$$h_{\mathrm{e}} = h + k_h \tag{20}$$

in which k_h is an experimentally determined quantity, in metres, which compensates for the combined effects of viscosity and surface tension.

10.5.2 Evaluation of C_{d} and k_h

For triangular weirs with notch angle α equal to $\pi/2$ radians (90°), Figure 8 shows experimentally determined values of C_{d} for a wide range of values of h/p and p/B. For $\alpha = \pi/2$ radians (90°), k_h has been shown to have a constant value of 0,000 85 m for a corresponding range of values of h/p and p/B.

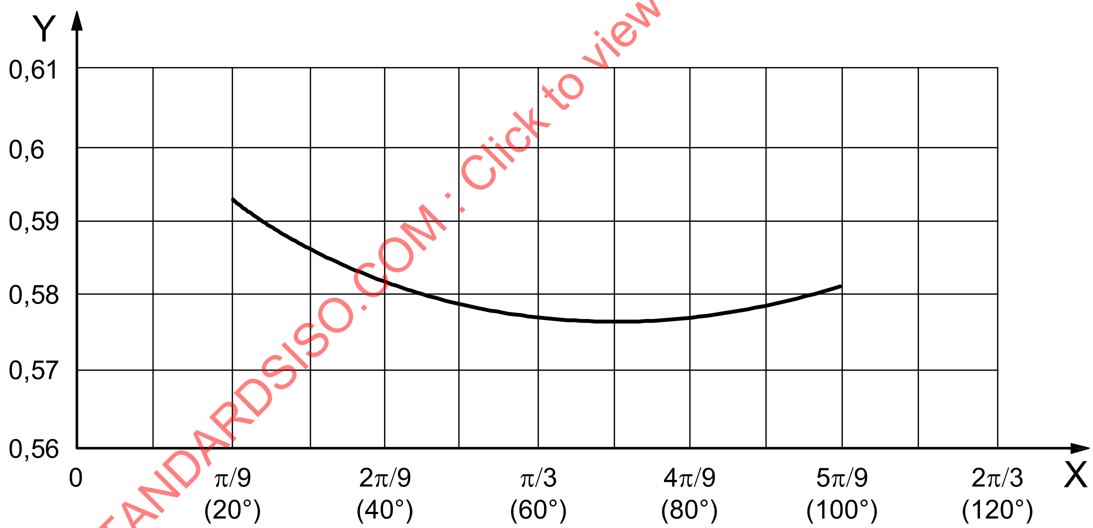


Key

X value of $\frac{h}{p}$

Y value of C_d

Figure 8 — Coefficient of discharge, C_d ($\alpha = 90°$)



Key

X value of notch angle, α (radians)

Y value of C_d

Figure 9 — Coefficient of discharge C_d related to notch angle α

For notch angles other than $\pi/2$ radians (90°), experimental data are insufficient to define C_d as a function of h/p and p/B. However, for weir notches which are small relative to the area of the approach channel, the velocity of approach is negligible and the effects of h/p and p/B are also negligible. For this condition (the so-called "fully-contracted" condition), Figure 9 shows experimentally determined values of C_d as a function of α alone. Corresponding values of k_h are shown in Figure 10.

10.5.3 Practical limitations on α, h/p, p/B, h and p

For reasons related to hazards of measurement-error and lack of experimental data, the following practical limits are applicable to use of the Kindsvater-Shen formula:

a) α shall be between $\pi/9$ and $5\ \pi/9$ radians (20° and 100°);

b) h/p shall be limited to the range shown on Figure 8 for $\alpha = \pi/2$ radians (90°); h/p shall be not greater than 0,35 for other values of α;

c) h shall be not less than 0,06 m;

d) p shall be not less than 0,09 m.

10.6 Formula for specific notch angles (fully-contracted weir)

The BSI [1)] equation is for three notch angles that have a special geometric relationship to each other:

a) tangent $\alpha/2 = 1$ ($\alpha = \pi/2$ radians or 90°);

b) tangent $\alpha/2 = 0{,}50$ ($\alpha = 0{,}927\ 3$ radian or 53° 8′);

c) tangent $\alpha/2 = 0{,}25$ ($\alpha = 0{,}489\ 9$ radian or 28° 4′).

The BSI discharge formula is:

$$Q = C\frac{8}{15}\tan\frac{\alpha}{2}\sqrt{2g}\,h_{\mathrm{e}}^{5/2} \tag{21}$$

and the experimentally determined values of C and Q for the condition of “full contraction” are shown in Tables E.1, E.2 and E.3.

Practical limitations applicable to the use of this formula are:

a) h/p shall be not greater than 0,4;

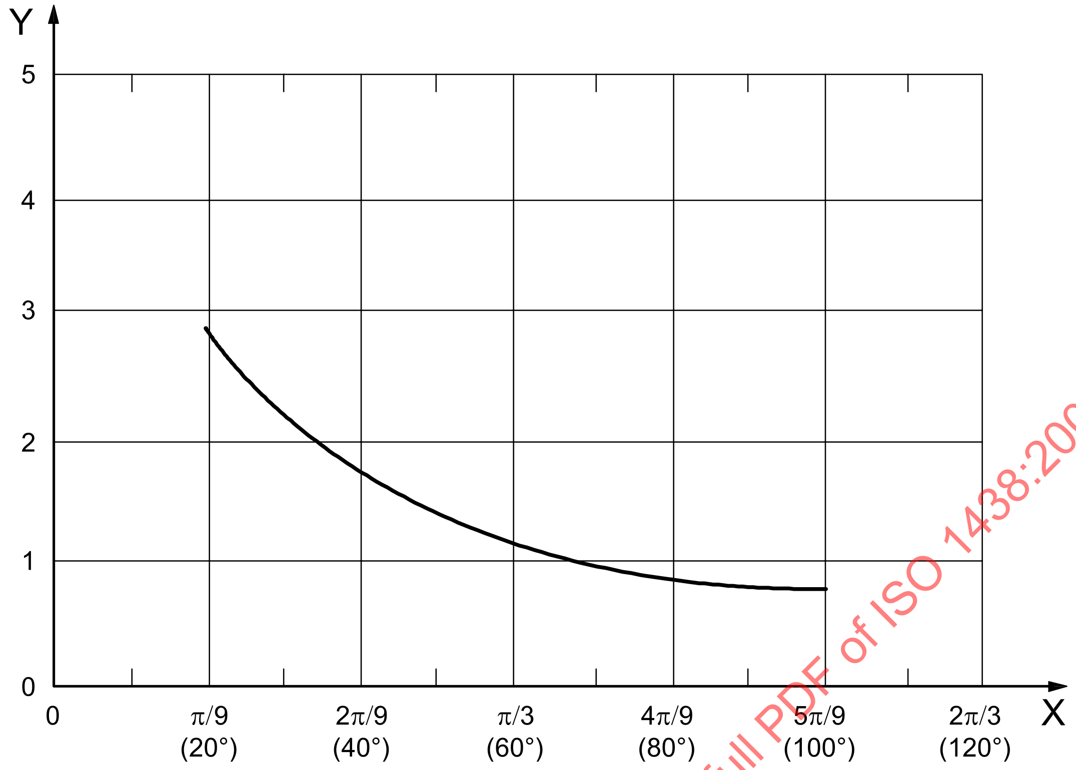
b) h/B shall be not greater than 0,2;

c) h shall be between 0,05 and 0,38 m;

d) p shall be not less than 0,45 m;

e) B shall be not less than 1,0 m.

1) British Standards Institution.



Key

X notch angle α

Y k_h, in millimetres

Figure 10 — Value of k_h related to notch angle α

10.7 Accuracy of discharge coefficients — Triangular-notch weirs

The accuracy of discharge measurements made with a triangular-notch thin-plate weir depends primarily on the accuracy of the head and notch-angle measurements and on the applicability of the discharge formula and coefficients used. If great care is exercised in meeting the construction, installation, and operational conditions specified in this International Standard, uncertainties (at 95 % confidence level) attributable to the coefficients of discharge will be not greater than 1,0 %. The combination of all uncertainties which contribute significantly to the uncertainty of discharge measurements is treated in Clause 11. Examples of estimated uncertainties in measured discharge are given in Clause 12.

11 Uncertainties of flow measurement

11.1 General

11.1.1 This clause provides information for the user of this International Standard to state the uncertainty of a measurement of discharge.

11.1.2 Annex C is an introduction to measurement uncertainty. It provides supporting information based on the *Guide to the expression of uncertainty in measurement* (hereafter referred to as the GUM)[5] and ISO/TS 25377 (hereafter referred to as the HUG)[4]. Refer to Annex C for definitions.

Former versions of this International Standard have expressed the uncertainty of discharge coefficient $u(C)$ at the 95 % level of confidence. This is equivalent to two standard deviations, or twice the value of standard uncertainty.

This version of ISO 1438-1, expresses discharge coefficient as standard uncertainty (one standard deviation) to be in accordance with the GUM.

Hydrometry requires measurements using various techniques, the results of which are used to calculate a value for flow. Annex D provides sample values for the various techniques. These are presented in tabular form with uncertainty estimates ascribed to each technique for the purpose of illustration only.

These sample values are not to be interpreted as norms of performance.

The example given in Clause 12 uses values from Annex D.

11.1.3 A measurement result comprises

i) an estimate of the measured value, with

ii) a statement of the uncertainty of the measurement.

11.1.4 A statement of the uncertainty of a flow measurement in a channel has four separate components of uncertainty:

i) uncertainty of the measurement of head in the channel;

ii) uncertainty of the dimensions of the structure;

iii) uncertainty of the discharge coefficient stated in this International Standard from laboratory calibration of the flow structure being considered;

iv) uncertainty of channel velocity distribution related to the velocity coefficient, C_v.

This clause does not accommodate component iv). It is assumed that the channel hydraulics are substantially equivalent to those existing in the calibration facility at the time of derivation of component iii) as defined in 6.3.3.

11.1.5 The estimation of measurement uncertainty associated with items i) and ii) of 11.1.4 is provided in Annex D.

Values taken from Annex D are used in the examples in Clause 12. These values are for illustrative purposed only, they should not be interpreted as norms of performance for the types of equipment listed. In practice, uncertainty estimates should be taken from test certificates for the equipment, preferably obtained from laboratories which are accredited to ISO/IEC 17025.

11.2 Combining measurement uncertainties

Refer to Clause C.7.

The proportion in which each flow equation parameter contributes to flow measurement uncertainty, $U(Q)$, is derived by analytical solution using partial differentials of the discharge equation.

For this purpose, the equations for rectangular and triangular forms have been simplified to:

$$Q_\text{r} = J_\text{r}\sqrt{g}\, C_\text{d}\, b_\text{e}\, h_\text{e}^{1,5} \tag{22}$$

$$Q_\text{t} = J_\text{t}\sqrt{g}\, C_\text{d} \tan\frac{\alpha}{2}\, h_\text{e}^{2,5} \tag{23}$$

where J is a numerical constant, dependent on the form of weir but not subject to error. The subscripts r and t denote the rectangular form and the triangular form of weir, respectively. From Equations (22) and (23), the dispersion of the value Q of the equation can be written:

$$\Delta Q_\mathrm{r} = J_\mathrm{r}\sqrt{g}\left(\frac{\partial Q_\mathrm{r}}{\partial C_\mathrm{d}}\Delta C_\mathrm{d} + \frac{\partial Q}{\partial b_\mathrm{e}}\Delta b_\mathrm{e} + \frac{\partial Q}{\partial h_\mathrm{e}}\Delta h_\mathrm{e}\right) \quad (24)$$

$$\Delta Q_\mathrm{t} = J_\mathrm{t}\sqrt{g}\left(\frac{\delta Q_\mathrm{t}}{\delta C_\mathrm{d}}\Delta C_\mathrm{d} + \frac{\partial Q_\mathrm{t}}{\delta \tan\left(\frac{\alpha}{2}\right)}\Delta \tan\left(\frac{\alpha}{2}\right) + \frac{\partial Q_\mathrm{t}}{\delta h_\mathrm{e}}\Delta h_\mathrm{e}\right) \quad (25)$$

where the partial derivatives are the sensitivity coefficients described in the HUG and where ΔQ is the dispersion of Q due to small dispersions of ΔC, Δb or $\Delta \tan\left(\frac{\alpha}{2}\right)$ and Δh_e. Evaluating the partial differentials and using Equations (22) and (23), the relationship can be written:

$$\frac{\Delta Q_\mathrm{t}}{Q_\mathrm{t}} = \frac{\Delta C_\mathrm{d}}{C_\mathrm{d}} + \frac{\Delta b_\mathrm{e}}{b_\mathrm{e}} + 1{,}5\frac{\Delta h_\mathrm{e}}{h_\mathrm{e}} \quad (26)$$

$$\frac{\Delta Q_\mathrm{t}}{Q_\mathrm{t}} = \frac{\Delta C_\mathrm{d}}{C_\mathrm{d}} + \frac{\Delta \tan\frac{\alpha}{2}}{\tan\frac{\alpha}{2}} + 2{,}5\frac{\Delta h_\mathrm{e}}{h_\mathrm{e}} \quad (27)$$

In uncertainty analysis, the values $\frac{\Delta Q}{Q}, \frac{\Delta b}{b}, \frac{\Delta C}{C}, \frac{\Delta \tan\frac{\alpha}{2}}{\tan\frac{\alpha}{2}}$ and $\frac{\Delta h}{h}$ are referred to as dimensionless standard uncertainties and have the notation $u^*(Q)$, $u^*(C)$, $u^*(b)$, $u^*\left[\tan\left(\frac{\alpha}{2}\right)\right]$ and $u^*(h)$.

Note, the value $u^*\left[\tan\left(\frac{\alpha}{2}\right)\right]$ is derived from the relationship:

$$\tan\left(\frac{\alpha}{2}\right) = \frac{b_\mathrm{t}}{2h_\mathrm{t}} \quad (28)$$

where b_t is the crest width and h_t is the height of the notch.

Since the uncertainties of b, α, C and h are independent of each other, probability requires summation in quadrature rather than a simple summation.

$$u_\mathrm{c}^*(Q)_\mathrm{r} = \sqrt{u^*(C_\mathrm{d})^2 + u^*(b_\mathrm{e})^2 + \left[1{,}5u^*(h_\mathrm{e})\right]^2} \quad (29)$$

$$u_\mathrm{c}^*(Q)_\mathrm{t} = \sqrt{u^*(C_\mathrm{d})^2 + u^*\left[\tan\left(\frac{\alpha}{2}\right)\right]^2 + \left[2{,}5u^*(h_\mathrm{e})\right]^2} \quad (30)$$

11.3 Uncertainty of discharge coefficient $u^*(C_d)$ for thin-plate weirs

The discharge coefficient C_d of Clauses 9 and 10 have been determined from a series of hydraulics tests using a high resolution calibration facility. From these tests, the values of discharge coefficient uncertainty, $u^*(C_d)$, are summarized in Table 2.

Table 2 — Values of discharge coefficient uncertainty, $u^*(C_d)$, against head, h

Type	Head, h	$u^*(C_d)$
Rectangular	$h < 1{,}0p$	0,75 %
Rectangular	$1{,}0p < h < 1{,}5p$	1,00 %
Rectangular	$1{,}5p < h < 2{,}5\,p$	1,50 %
Triangular	—	0,5 %

11.4 The uncertainty budget

In reports, an uncertainty budget table may be presented (or referenced) to provide the following information for each source of uncertainty:

a) the method of evaluation (from Annex C);

b) the determined value of standard uncertainty $u^*(C_d)$, $u^*\left[\tan\left(\frac{\alpha}{2}\right)\right]$ and $u^*(h_e)$ including datum uncertainly of $u^*(h_e)$;

c) the relative sensitivity coefficients, Equations (26) and (27).

The values for each source are then applied according to Equation (29) or Equation (30) to give the combined standard uncertainty, $u^*(Q)$.

The expanded uncertainty $U^*(Q)$ for a confidence level of 95 % is calculated using Table C.1.

It is customary to present these steps in tabular form with one row for each source and a column for each of the items a) to c) above.

The table may include, where appropriate, the critical thinking behind the subjective allocation of uncertainty to the quantities b and h. This section of the table may be replicated for a range of values of h_1 to determine a relationship between $u^*(Q)$ and h_1.

12 Example

12.1 General

In presenting examples, the equations given in Clauses 9 and 10 define the relationship between the parameters which determine flow rate.

Uncertainty of the discharge coefficient is a fundamental uncertainty and is defined in 11.3. To complete an overall uncertainty estimation, practical estimations shall be made of the head measurement uncertainty and the uncertainty of the measurement of physical dimensions.

Annex D provides a consistent framework for evaluating these uncertainties for the commonly used measurement techniques.

One such technique is selected in 12.3 for the example that follows.

12.2 Characteristics — Gauging structure

The example relates to modular flow conditions for a 90° V-notch weir. The crest height p above the bed of the approach channel is 0,151 m. The channel is 0,503 m wide. The angle of the V-notch is estimated to lie between 89,5° and 90,5°.

12.3 Characteristics — Gauged head instrumentation

In this example, a pressure transducer is used to determine head. The transducer is located in the approach channel about 1 m upstream of the weir.

i) The signal indicates a head of 0,212 m. Referring to Annex D, the measurement uncertainty from the table, at this head, is $u(h_1) = 0{,}002$ m.

ii) The transducer is susceptible to drift over a period of time. Over a period of time, it has been noted that the nominal datum signal varies in the range 0,000 m to 0,007 m. Datum uncertainty is estimated according to the rectangular distribution Equation (C.5).

$$u(E) = \frac{1}{\sqrt{3}}\left(\frac{0{,}007 - 0{,}000}{2}\right)$$

$$u(E) = 0{,}002 \text{ m}$$

12.4 Discharge coefficient

The value of the gauged head discharge coefficient is determined from Figure 8 for the 90° V-notch weir. The key ratios of h/p and p/B are:

$$\frac{h}{p} = \frac{0{,}212}{0{,}151} = 1{,}40$$

$$\frac{p}{B} = \frac{0{,}151}{0{,}503} = 0{,}30$$

From which $C_d = 0{,}600$.

12.5 Discharge estimate

The flow rate is calculated from Equation (18):

$$Q_t = C_d \frac{8}{15} \tan\frac{\alpha}{2} \sqrt{2g}\, h_e^{5/2}$$

where $h_e = h + k_h = 0{,}212 + 0{,}000\,85$

$$Q_t = 0{,}600 \times 0{,}533\,3 \times 4{,}429 \times 1 \times 0{,}212\,85^{2{,}5}$$

$$\therefore Q_t = 0{,}029\,6 \text{ m}^3\text{/s}$$

12.6 Uncertainty statement

12.6.1 From Table 2, the value for uncertainty of the discharge coefficient is:

$$u^*(C) = 0{,}50\ \%$$

12.6.2 Using Equation (C.4), the value of uncertainty of the V-angle may be written:

$$u\left[\tan\left(\frac{\alpha}{2}\right)\right] = \frac{1}{\sqrt{6}}\left[\frac{\tan\left(\frac{90{,}5}{2}\right) - \tan\left(\frac{89{,}5}{2}\right)}{2}\right]$$

$$= 0{,}003\ 6$$

$$\text{or } u^*\left[\tan\left(\frac{\alpha}{2}\right)\right] = 100 \times \frac{0{,}003\ 6}{\tan\left(\frac{90}{2}\right)} = 0{,}36\ \%$$

12.6.3 The combined uncertainty of gauged head $u(h)$, calculated in 12.3, is combined with instrumentation measurement uncertainty and datum measurement uncertainty.

$$u(h) = \sqrt{(0{,}002)^2 + (0{,}002)^2}\ \text{m}$$

$$u(h) = 0{,}002\ 8\ \text{m}$$

$$u^*(h) = \frac{0{,}002\ 8}{0{,}212} \times 100$$

$$u^*(h) = 1{,}32\ \%$$

12.6.4 The combined uncertainty estimate is determined from Equation (30).

$$u_c^*(Q) = \sqrt{u^*(C_e)^2 + u^*\left[\tan\left(\frac{\alpha}{2}\right)\right]^2 + \left[2{,}5u^*(h_e)\right]^2}$$

$$u_c^*(Q) = \sqrt{0{,}50^2 + 0{,}36^2 + (2{,}5 \times 1{,}32)^2}$$

$$u_c^*(Q) = 3{,}35\ \%$$

Therefore, at the 95 % confidence level:

$$u_c^*(Q) = 3{,}35 \times 2 = 6{,}7\ \%$$

NOTE This estimate is dominated by the contribution from head measurement uncertainty and assumes sufficient measurement samples.

12.6.5 The conventional statement of discharge is therefore:

0,029 3 m^3/s with an uncertainty of 6,7 % at the 95 % level of confidence based on a coverage factor of $k = 2$.

12.6.6 The uncertainty budget for the example could be expressed as in Table 3.

Table 3 — Uncertainty budget for the example

	Type/ Evaluation	u, u^* Value	Sensitivity coefficients	Comment
$u^*(C_d)$	B/Normal	0,5 %	1,0	From laboratory tests
$u^*[\tan(\alpha/2)]$	B/Triangular	0,36 %	1,0	Using C.6.2
$u(E)$	B/Rectangular	0,002 m	—	Using C.6.3
$u(h_1)$	B/Rectangular	0,002 m	—	From Table D.1
$u^*(h_1)$	Combined	1,32 %	2,5	From 12.6.3
$u_c^*(Q)$	Combined	3,35 %	—	Using Equation (6)

Annex A
(informative)

Flow measurement with small weir tanks

Whenever possible, weir tanks conforming to 6.3.3 should be used to measure flow in the field. When the highest accuracy is not required or where site conditions make it difficult to install or operate large tanks satisfactorily, smaller tanks may be used.

There is a limited amount of data on how the discharge coefficients of weirs are affected by the size of the tank, as well as by non-standard head-measuring positions, asymmetric and unsteady flow conditions at entry and sediment deposits. Further information can be obtained from *The performance of weir tanks fitted with V-notch and rectangular thin-plate weirs* [2)].

In order to give some guide to the effect that a reduction in the size of the weir tank will have, values of the discharge coefficient have been tabulated for seven different sizes of weir tank. Table A.1 gives values of C in the BSI formula for a 90° V-notch and of C_d in the Kindsvater-Carter formula for a contracted rectangular-notch.

Some indication of the influence of sediment deposit is given in Table A.2, which shows values of C_d for a tank with dimensions conforming to 6.3.3 but with differing amounts of sediment deposited against the weir plate. The uncertainty of these coefficients is approximately 1 %.

Within the range of tank sizes and heads covered in Table A.1, the location of the head-measuring device is relatively unimportant. Positions between 100 mm and 720 mm upstream of the weir produce discharge coefficients which vary by less than 0,5 %. Heads should not be measured, however, near the inlet baffle or in the downstream corner of a narrow tank.

Table A.1 — Discharge coefficients for 90° V-notches and rectangular notches in small weir tanks

Tank size (length, width, height)	C **values for 90° V-notches** [a]			C_d **values for rectangular notches** [b]		
	Head (h) mm			**Head** (h) mm		
m	**115**	**150**	**180**	**65**	**100**	**135**
2,62 × 0,92 × 0,45	0,593	0,592	0,587	0,609	0,592	0,588
1,50 × 0,92 × 0,45	0,603	0,592	0,587	0,604	0,592	0,588
1,00 × 0,92 × 0,45	0,603	0,592	0,587	0,600	0,590	0,588
2,62 × 0,75 × 0,45	0,597	0,592	0,590	0,606	0,593	0,588
2,62 × 0,50 × 0,45	0,605	0,596	0,595	0,611	0,598	0,598
2,62 × 0,92 × 0,30	0,600	0,590	0,586	0,606	0,592	0,588
2,62 × 0,92 × 0,15	0,602	0,597	0,593	0,613	0,598	0,595

a $Q = C\frac{8}{15}\sqrt{2g}\, h^{5/2}$

b $Q = C\frac{2}{3}\sqrt{2g}\, b_e\, h_e^{3/2}$

2) Available from Hydraulics Research Ltd., Wallingford, Oxon., England, as Report No. EX1243, 1985.

Table A.2 — Discharge coefficients for rectangular notches in small weir tanks with sediment deposits

Tank size (length, width, height)	**Max. level of deposits relative to weir crest**	C_d **values for rectangular notches** [a]		
		Head (h) mm		
m	mm	**65**	**100**	**135**
2,62 × 0,92 × 0,45	− 150	0,605	0,591	0,588
	− 40	0,606	0,597	0,590
	− 40 (+ 100 at sides)	0,613	0,601	0,595

[a] $Q = C\frac{2}{3}\sqrt{2g}\, b_e\, h_e^{3/2}$

Annex B
(informative)

Guide to the design and installation of a flow straightener

A flow straightener may be used for reducing the approach channel length.

The purpose of a flow straightener is to modify the flow in a shortened approach channel so that the velocity distribution of the flow is normal and steady.

Subclause 6.3.3 and Figure 1 specify a normal velocity distribution.

A flow straightener should consist of several perforated plates (at least four), installed vertically and perpendicular to the flow direction with a minimum spacing of 0,2 m between adjacent plates. The percentage of the open area of each plate should be between 40 % and 60 % inclusive.

Figure B.1 shows an example of perforation. Holes are distributed in a staggered formation; in the example, the distance between the centres of two neighbouring holes is 30 mm; the hole diameter is 20 mm. This gives a percentage of open area equal to 40,31 %.

The plates should be thick and sufficiently strong to sustain the force exerted by the channel flow. The dimension of the holes may be varied in accordance with the channel width, provided that the spacing between the plates is adjusted in proportion to the hole diameter.

The straightener plates may be fixed on the approach channel, either with the perforations of the different plates aligned on the general direction of the stream (Figure B.2), or with them positioned in a staggered formation, provided that the distance between adjacent plates is large compared with the hole diameter (Figure B.3).

Dimensions in millimetres

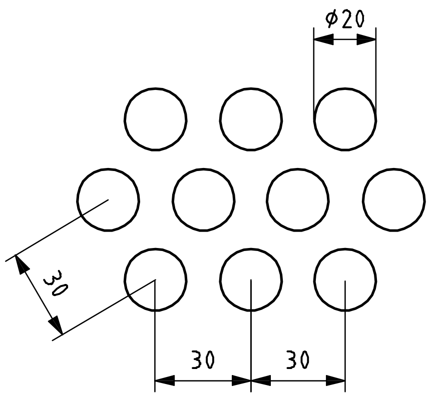


Figure B.1 — Example of perforation

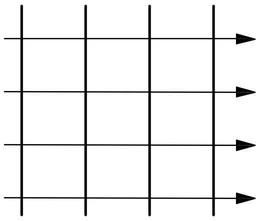


Figure B.2 — Aligned perforations

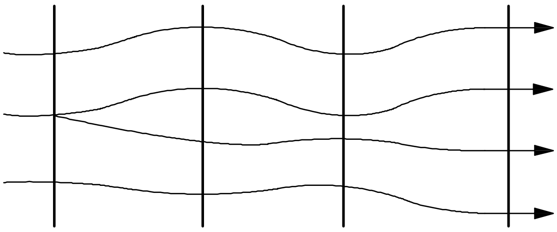


Figure B.3 — Staggered perforations

Annex C
(informative)

Introduction to measurement uncertainty

C.1 General

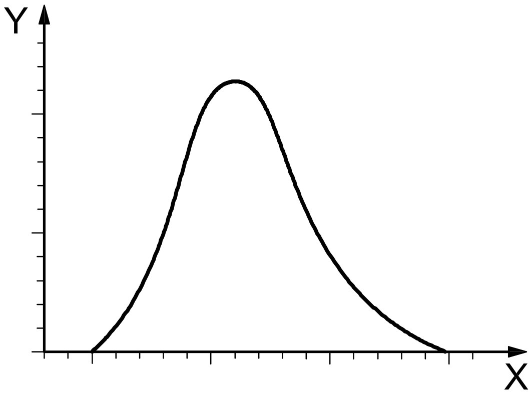
Results of measurements or analysis cannot be exact. The discrepancy between the true value, which is unknowable, and the measured value is the measurement error. The concept of uncertainty is a way of expressing this lack of knowledge. For example, if water is controlled to flow at a constant rate, then a flow meter will exhibit a spread of measurements about a mean value. If attention is not given to the uncertain nature of data, incorrect decisions can be made which have financial or judicial consequences. A realistic statement of uncertainty enhances the quality of information, making it more useful.

The uncertainty of a measurement represents a dispersion of values that could be attributed to it. Statistical methods provide objective values based on the application of theory.

Standard uncertainty is defined as:

Standard uncertainty equates to a dispersion of measurements expressed as a standard deviation.

From this definition, uncertainty can be readily calculated for a set of set of measurements.

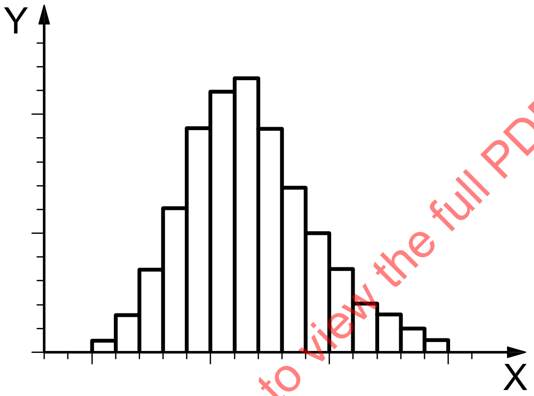


a)

Key

X flow value

Y probability

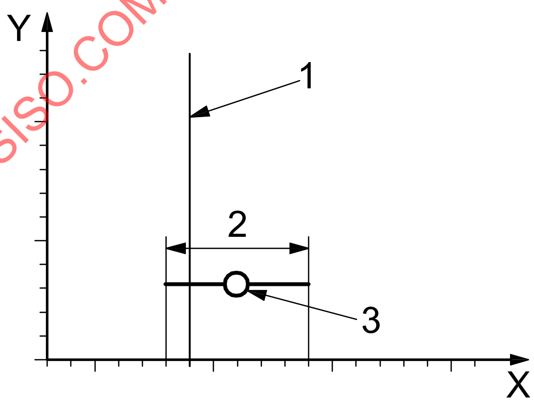


b)

Key

X flow value

Y number of samples



c)

Key

1 limit

2 standard deviation

3 mean value

X flow value

Y number of samples

Figure C.1 — Pictorial representation of some uncertainty paramaters

Figure C.1 a) shows the probability that a measurement of flow under steady conditions takes a particular value due to the uncertainties of various components of the measurement process, in the form of a probability density function.

Figure C.1 b) shows sampled flow measurements, in the form of a histogram.

Figure C.1 c) shows standard deviation of the sampled measurements compared with a limiting value. The mean value is shown to exceed the limiting value but is within the band of uncertainty (expressed as the standard deviation about the mean value).

C.2 Confidence limits and coverage factors

For a normal probability distribution, analysis shows that 68 % of a large set of measurements lies within one standard deviation of the mean value. Thus, standard uncertainty is said to have a 68 % level of confidence.

However, for some measurement results, it is customary to express the uncertainty at a level of confidence which will cover a larger portion of the measurements: for example at a 95 % level of confidence (see Figure C.4). This is done by applying a factor, the coverage factor k, to the computed value of standard uncertainty.

For a normal probability distribution, 95,45 % (effectively 95 %) of the measurements are covered for a value of $k = 2$. Thus, uncertainty at the 95 % level of confidence is twice the standard uncertainty value.

In practice, measurement variances rarely follow closely the normal probability distribution. They may be better represented by triangular, rectangular or bimodal probability distributions and only sometimes approximate to the normal distribution.

So a probability distribution must be selected to model the observed variances. To express the uncertainty of such models at the 95 % confidence limit requires a coverage factor that represents 95 % of the observations. However, the same coverage factor, $k = 2$, is used for all models. This simplifies the procedure while ensuring consistency of application within tolerable limits.

C.3 Random and systematic error

The terms "random" and "systematic" have been applied in hydrometric standards to distinguish between i) random error that represent an inherent dispersion of values under steady conditions, and ii) systematic errors that are associated with inherent limitations of the means of determining the measured quantity.

A difficulty with the concept of systematic error is that systematic error cannot be determined without pre-knowledge of true values. If its existence is known or suspected, then steps must be taken to minimize such error either by recalibration of equipment or by reversing its effect in the calculation procedure. At which point, systematic error contributes to uncertainty in the same way as random components of uncertainty.

For this reason, the GUM does not distinguish between the treatment of random and systematic uncertainties. Generally, when determining a single discharge, random errors dominate and there is no need to separate random and systematic errors. However, where (say) totalized volume is established over a long time base, the systematic errors, even when reduced, can remain dominant in the estimation of uncertainty.

C.4 Measurement standards

The GUM and the HUG provide rules for the application of the principles of measurement uncertainty: in particular on the identification of components of error, the quantification of their corresponding uncertainties and how these are combined using methods derived from statistical theory into an overall result for the measurement process.

The components of uncertainty are characterized by estimates of standard deviations. There are two methods of estimation:

a) **Type-A estimation** (by statistical analysis of repeated measurements from which an equivalent standard deviation is derived)

   This process may be automated in real-time for depth or for velocity measurement.

b) **Type-B estimation** (by ascribing a probability distribution to the measurement process)

   This is applicable to:

   1) human judgement of a manual measurement (distance or weight),

   2) manual readings taken from instrumentation (manufacturer's statement), or

   3) calibration data (from manufacturer).

C.5 Evaluation of Type-A uncertainty

Defined in C.1, the term "standard uncertainty" equates to a dispersion of measurements expressed as a standard deviation. Thus, any single measurement of a set of n measurements has by definition an uncertainty:

$$u(x) = t_{\mathrm{e}}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{C.1}$$

where $\bar{x}$ is the best estimate of the true mean:

$$\bar{x} = \frac{1}{n}\left(x_1 + x_2 + ...x_n\right) \tag{C.2}$$

and t_{e} is a factor derived from statistical theory to account for the increased uncertainty when small numbers of measurements are available: refer to Table C.1.

If, instead of a single measurement from the set, the uncertainty is to apply to the mean of all n values, then:

$$u(\bar{x}) = \frac{t_{\mathrm{e}}}{\sqrt{n}}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{C.3}$$

For continuous measurement, Type-A evaluations may be derived as a continuous variable from the primary measurement, i.e. from water level or water velocity.

By taking average values over large numbers, n, of measurements, the uncertainty of the mean value $u\left(\bar{x}\right)$ is reduced by a factor of $\frac{1}{\sqrt{n}}$ compared to the uncertainty $u(x)$ of an individual measurement. For this reason, monitoring equipment should specify measurement performance in terms including both $u\left(\bar{x}\right)$ and $u(x)$ to show the extent to which averaging is applied.

Table C.1 — t_e factors at 90 %, 95 % and 99 % confidence levels

Degrees of freedom [a]	Confidence level %		
	90	95	99
1	6,31	12,71	63,66
2	2,92	4,30	9,92
3	2,35	3,18	5,84
4	2,13	2,78	4,60
5	2,02	2,57	4,03
10	1,81	2,23	3,17
15	1,75	2,13	2,95
20	1,72	2,09	2,85
25	1,71	2,06	2,79
30	1,70	2,04	2,75
40	1,68	2,02	2,70
60	1,67	2,00	2,66
100	1,66	1,98	2,63
Infinite	1,64	1,96	2,58

[a] In general, the number of terms in a sum minus the number of constraints on the terms of the sum (GUM).

C.6 Evaluation of Type-B uncertainty

C.6.1 General

When there is no access to a continuous stream of measured data or if a large set of measurements is not available, then the type-B method of estimation is used to:

i) assign a probability distribution to the measurement process to represent the probability of the true value being represented by any single measured value;

ii) define upper and lower bounds of the measurement; and then

iii) determine a standard uncertainty from a standard deviation implied by the assigned probability distribution.

The Type-B methods allow estimates of upper and lower bounding values to be used to derive the equivalent standard deviation.

Four probability distributions are described in the GUM and in C.6.2 to C.6.5.

C.6.2 The triangular distribution

The triangular distribution is represented in Figure C.2.

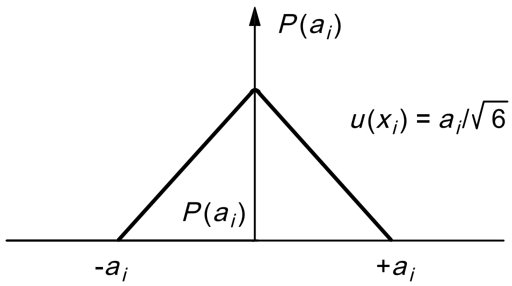


Figure C.2 — The triangular distribution

$$u\left(x_{\text{mean}}\right) = \frac{1}{\sqrt{6}}\left(\frac{x_{\max} - x_{\min}}{2}\right) \quad \text{(C.4)}$$

This usually applies to manual measurements where the mean value is most likely to be closer to the true value than others between the discernible upper and lower limits of the measurement.

C.6.3 The rectangular distribution

The rectangular distribution is represented in Figure C.3.

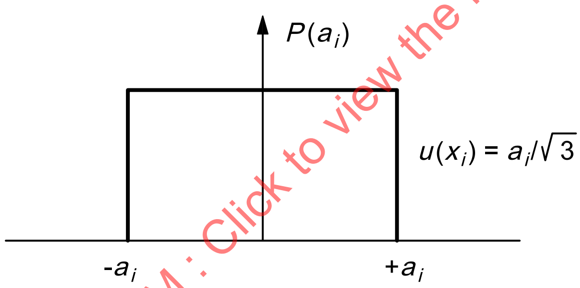


Figure C.3 — The rectangular distribution

$$u\left(x_{\text{mean}}\right) = \frac{1}{\sqrt{3}}\left(\frac{x_{\max} - x_{\min}}{2}\right) \quad \text{(C.5)}$$

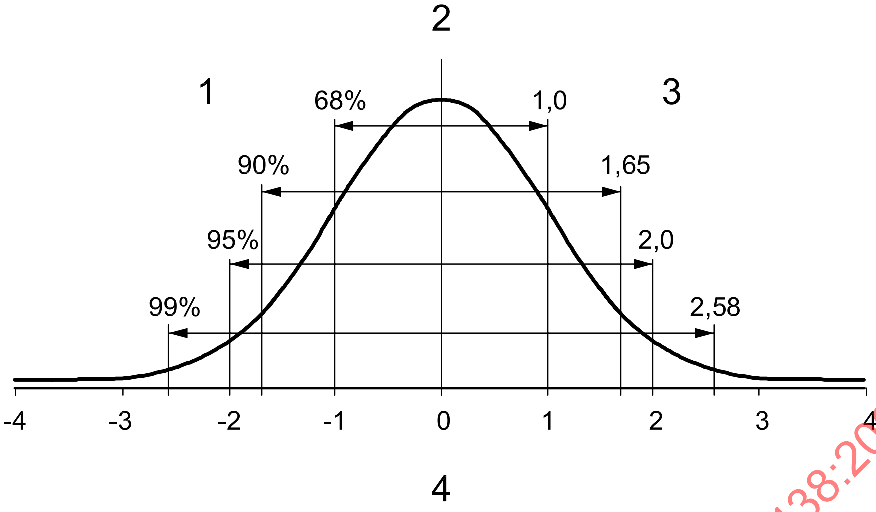
This probability distribution is usually applied to the resolution limit of the measurement instrumentation (i.e. the displayed resolution or the resolution of internal analogue/digital converters).

However, this is not the only source of uncertainty of measurement equipment. There may be uncertainty arising from the measurement algorithm used and/or from the calibration process.

If the equipment measures relative values, then there will also be uncertainty in the determination of its datum.

C.6.4 The normal probability distribution

The normal probability distribution is represented in Figure C.4.



Key

1 percent of readings in bandwidth

2 probability

3 coverage factor

4 standard deviations

Figure C.4 — The normal probability distribution

$$u(x_{\text{mean}}) = \frac{u(\text{specified})}{k} \quad \text{(C.6.)}$$

where k is the coverage factor applying to the specified uncertainty value.

These are uncertainty statements based on “off-line” statistical analysis, usually as part of a calibration process where they have been derived using a Type-A process. When expressed as standard uncertainty, the uncertainty value is to be used directly with an equivalent coverage factor of $k = 1$.

C.6.5 The bimodal probability distribution

The bimodal probability distribution is represented in Figure C.5.

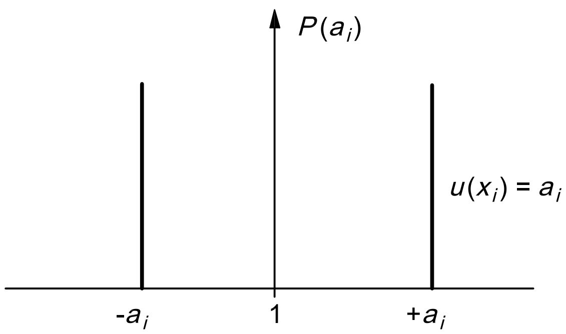


Figure C.5 — The bimodal probability distribution

$$u(x_{\text{mean}}) = \frac{(x_{\text{max}} - x_{\text{min}})}{2} \quad \text{(C.7)}$$

Measurement equipment with hysteresis can only exhibit values at the upper and lower bounds of the measurement.

An example of this is the float mechanism where friction and surface tension combine to cause the float to move in finite steps.

C.7 Combined uncertainty value, u_c

For most measurement systems, a measurement result is derived from several variables. For example, flow measurement, Q, in a rectangular channel can be expressed as a function of independent variables:

$$Q = b \times h \times \bar{V} \tag{C.8}$$

where

b is the channel width;

h is the depth of water in the channel;

$\bar{V}$ is the mean velocity.

These three components are measured independently and combined to determine a value for Q.

Just as b, h and $\bar{V}$ are combined to determine the value Q, so each component of uncertainty must be combined to determine a value for $u_c(Q)$. This is done by evaluating the sensitivity of Q to small change, Δ, in b, h or V. Thus:

$$\Delta Q = \frac{\partial Q}{\partial b}\Delta b + \frac{\partial Q}{\partial h}\Delta h + \frac{\partial Q}{\partial \bar{V}}\Delta \bar{V} \tag{C.9}$$

where the partial differentials, $\frac{\partial Q}{\partial b}$, $\frac{\partial Q}{\partial h}$ and $\frac{\partial Q}{\partial \bar{V}}$ are sensitivity coefficients. For the equation $Q = b \times h \times \bar{V}$, this is equal to:

$$\frac{\Delta Q}{Q} = \frac{\Delta b}{b} + \frac{\Delta h}{h} + \frac{\Delta \bar{V}}{\bar{V}} \tag{C.10}$$

In uncertainty analysis, the values $\frac{\Delta Q}{Q}$, $\frac{\Delta b}{b}$, $\frac{\Delta h}{h}$ and $\frac{\Delta \bar{V}}{\bar{V}}$ correspond to dimensionless standard uncertainties. They are given the notation $u_c{*}(Q)$, $u{*}(b)$, $u{*}(h)$ and $u{*}(V)$.

Since the uncertainties of b, V and h are independent of each other, probability considerations require summation in quadrature.

$$u_c^*(Q) \cong \sqrt{u^*(\bar{V})^2 + u^*(b)^2 + u^*(h)^2} \tag{C.11}$$

Annex D
(informative)

Sample measurement performance for use in hydrometric worked examples

Table D.1 — Sample measurement performance for use in hydrometric worked examples

Measurement technologies		Comment	Symbol	Uncertainty Options		Installed equipment to have corresponding values certified by the manufacturer									
						Nominal range of measurement					Corresponding standard uncertainty (68 % confidence limit)				
				A	B	Minimum	25 %	50 %	75 %	Maximum	Minimum	25 %	50 %	75 %	Maximum
Velocity (continuous)															
Point Velocity	Propeller	Calibration certificate	$u(V)$	YES	Normal	0,005 m/s	1,250 m/s	2,500 m/s	3,750 m/s	5,000 m/s	0,000 5 m/s	0,010 m/s	0,022 m/s	0,030 m/s	0,040 m/s
	Electromagnetic	Calibration certificate	$u(V)$	YES	Normal	0,005 m/s	0,750 m/s	1,500 /s	2,250 m/s	3,000 m/s	0,000 5 m/s	0,010 m/s	0,018 m/s	0,025 m/s	0,025 m/s
Path velocity	Time of flight sonar	Sonic velocity path angle	$u(V)$	YES	Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
	Gated Doppler sonar	Particle dependent - low velocity resolution	$u(V)$	YES	Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
	Sonar correlation	Particle dependent	$u(V)$	YES	Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
Section Velocity	EM	To be calibrated *in situ*	$u(V)$		Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
Water level (continuous)															
Relative Datum (must be applied to all methods)		Manual process	$u(E)$		Triangular	Not applicable	0,500 m	1,000 m	1,500 m	2,000 m	0,001 m	0,001 m	0,001 5 m	0,001 5 m	0,001 5 m
In-contact methods	Encoder/float system	Requires regular maintenance	$u(h_1)$		Bimodal	Extension 0,200 m	Extension 1,250 m	Extension 2,500 m	Extension 3,750 m	Extension 5,000 m	0,001 5 m	0,002 0 m	0,002 0 m	0,002 5 m	0,002 5 m
	Pressure transducer	Datum value drift	$u(h_1)$		Rectangular	0,010 m	0,500 m	1,000 m	1,500 m	2,000 m	0,002 m	0,002 m	0,002 5 m	0,002 5 m	0,003 0 m
	Sonar	Surface wave effects	$u(h_1)$	YES	Rectangular	0,050 m	0,500 m	1,000 m	1,500 m	2,000 m	0,001 m	0,001 m	0,001 5 m	0,001 5 m	0,001 5 m
Non-contact methods	Pulse echo ultrasound	Surface wave effects Air temperature Compensation	$u(R)$	YES	Rectangular	Range 0,300 m	Range 1,250 m	Range 2,500 m	Range 3,750 m	Range 5,000 m	0,002 m	0,004 m	0,010 m	0,025 m	0,060 m
	Pulse echo opto/radar	Surface wave effects	$u(R)$		Rectangular	Range 0,300 m	Range 1,250 m	Range 2,500 m	Range 3,750 m	Range 5,000 m	0,002 m	0,004 m	0,010 m	0,025 m	0,060 m
Cross-section profile (distance measurement)															
	Natural channels	Sonar or dip gauging/GPRS or tracking	$u(B)$		Rectangular	0,500 m	5,000 m	10,000 m	15,000 m	20,000 m	0,002 m	0,020 m	0,060 m	0,100 m	0,200 m
	Man-made channels	Manual measurement	$u(B)$		Triangular	Not applicable	0,500 m	1,000 m	1,500 m	2,000 m	0,001 m	0,001 m	0,0015 m	0,0015 m	0,0015 m

Annex E
(informative)

Specimen tables

Table E.1 — Discharge of water over a V-notch with tan $\frac{\alpha}{2} = 1$ ($\alpha = \frac{\pi}{2}$ radians or 90°)

$$Q = 2{,}362\ 5\ C_d h^{5/2}$$

(g = 9,806 6 m/s^2)

Head h m	Coefficient C_d	Discharge Q m^3/s × 10^{-1}
0,060	0,603 2	0,012 57
0,061	0,602 8	0,013 09
0,062	0,602 3	0,013 62
0,063	0,601 9	0,014 17
0,064	0,601 5	0,014 73
0,065	0,601 2	0,015 30
0,066	0,600 8	0,015 88
0,067	0,600 5	0,016 48
0,068	0,600 1	0,017 10
0,069	0,599 8	0,017 72
0,070	0,599 4	0,018 36
0,071	0,599 0	0,019 01
0,072	0,598 7	0,019 67
0,073	0,598 3	0,020 35
0,074	0,598 0	0,021 05
0,075	0,597 8	0,021 76
0,076	0,597 5	0,022 48
0,077	0,597 3	0,023 22
0,078	0,597 0	0,023 97
0,079	0,596 7	0,024 73
0,080	0,596 4	0,025 51
0,081	0,596 1	0,026 30
0,082	0,595 8	0,027 10
0,083	0,595 5	0,027 92
0,084	0,595 3	0,028 76
0,085	0,595 0	0,029 61
0,086	0,594 8	0,030 48
0,087	0,594 5	0,031 36
0,088	0,594 2	0,032 25
0,089	0,594 0	0,033 16
0,090	0,593 7	0,034 09
0,091	0,593 5	0,035 03
0,092	0,593 3	0,035 98
0,093	0,593 1	0,036 96
0,094	0,592 9	0,037 95
0,095	0,592 7	0,038 95
0,096	0,592 5	0,039 97
0,097	0,592 3	0,041 01
0,098	0,592 1	0,042 06
0,099	0,591 9	0,043 12
0,100	0,591 7	0,044 20
0,101	0,591 4	0,045 30
0,102	0,591 2	0,046 41
0,103	0,591 0	0,047 54
0,104	0,590 8	0,048 69
0,105	0,590 6	0,049 85
0,106	0,590 4	0,051 03
0,107	0,590 2	0,052 22
0,108	0,590 1	0,053 44
0,109	0,589 9	0,054 67

Table E.1 (*continued*)

Head h m	Coefficient C_d	Discharge Q $m^3/s \times 10^{-1}$
0,110	0,589 8	0,055 92
0,111	0,589 7	0,057 19
0,112	0,589 6	0,058 47
0,113	0,589 4	0,059 77
0,114	0,589 2	0,061 08
0,115	0,589 1	0,062 42
0,116	0,589 0	0,063 77
0,117	0,588 9	0,065 14
0,118	0,588 8	0,066 53
0,119	0,588 6	0,067 93
0,120	0,588 5	0,069 35
0,121	0,588 3	0,070 79
0,122	0,588 2	0,072 24
0,123	0,588 1	0,073 72
0,124	0,588 0	0,075 22
0,125	0,588 0	0,076 73
0,126	0,587 9	0,078 27
0,127	0,587 8	0,079 82
0,128	0,587 7	0,081 39
0,129	0,587 6	0,082 98
0,130	0,587 6	0,084 58
0,131	0,587 5	0,086 21
0,132	0,587 4	0,087 85
0,133	0,587 3	0,089 51
0,134	0,587 2	0,091 19
0,135	0,587 2	0,092 89
0,136	0,587 1	0,094 61
0,137	0,587 0	0,096 34
0,138	0,586 9	0,098 10
0,139	0,586 9	0,099 87
0,140	0,586 8	0,101 67
0,141	0,586 7	0,103 48
0,142	0,586 7	0,105 32
0,143	0,586 6	0,107 17

Head h m	Coefficient C_d	Discharge Q $m^3/s \times 10^{-1}$
0,144	0,586 6	0,109 04
0,145	0,586 5	0,110 93
0,146	0,586 4	0,112 84
0,147	0,586 3	0,114 76
0,148	0,586 2	0,116 71
0,149	0,586 2	0,118 67
0,150	0,586 1	0,120 66
0,151	0,586 1	0,122 67
0,152	0,586 0	0,124 71
0,153	0,586 0	0,126 76
0,154	0,585 9	0,128 83
0,155	0,585 9	0,130 93
0,156	0,585 9	0,133 04
0,157	0,585 8	0,135 17
0,158	0,585 8	0,137 32
0,159	0,585 7	0,139 50
0,160	0,585 7	0,141 69
0,161	0,585 7	0,143 91
0,162	0,585 6	0,146 14
0,163	0,585 6	0,148 40
0,164	0,585 5	0,150 67
0,165	0,585 5	0,152 97
0,166	0,585 5	0,155 29
0,167	0,585 4	0,157 63
0,168	0,585 4	0,159 99
0,169	0,585 3	0,162 37
0,170	0,585 3	0,164 77
0,171	0,585 3	0,167 19
0,172	0,585 2	0,169 64
0,173	0,585 2	0,172 10
0,174	0,585 1	0,174 59
0,175	0,585 1	0,177 09
0,176	0,585 1	0,179 63
0,177	0,585 1	0,182 19

Table E.1 (*continued*)

Head h m	Coefficient C_d	Discharge Q $m^3/s \times 10^{-1}$
0,178	0,585 1	0,184 78
0,179	0,585 1	0,187 38
0,180	0,585 1	0,190 01
0,181	0,585 1	0,192 65
0,182	0,585 0	0,195 31
0,183	0,585 0	0,198 00
0,184	0,585 0	0,200 71
0,185	0,585 0	0,203 45
0,186	0,585 0	0,206 21
0,187	0,585 0	0,208 99
0,188	0,585 0	0,211 80
0,189	0,585 0	0,214 63
0,190	0,585 0	0,217 48
0,191	0,585 0	0,220 34
0,192	0,584 9	0,223 22
0,193	0,584 9	0,226 12
0,194	0,584 9	0,229 06
0,195	0,584 9	0,232 03
0,196	0,584 9	0,235 01
0,197	0,584 9	0,238 02
0,198	0,584 9	0,241 06
0,199	0,584 9	0,244 11
0,200	0,584 9	0,247 19
0,201	0,584 9	0,250 28
0,202	0,584 8	0,253 39
0,203	0,584 8	0,256 52
0,204	0,584 8	0,259 69
0,205	0,584 8	0,262 88
0,206	0,584 8	0,266 10
0,207	0,584 8	0,269 34
0,208	0,584 8	0,272 61
0,209	0,584 8	0,275 90
0,210	0,584 8	0,279 21

Head h m	Coefficient C_d	Discharge Q $m^3/s \times 10^{-1}$
0,211	0,584 8	0,282 54
0,212	0,584 8	0,285 88
0,213	0,584 7	0,289 24
0,214	0,584 7	0,292 64
0,215	0,584 7	0,296 07
0,216	0,584 7	0,299 53
0,217	0,584 7	0,303 01
0,218	0,584 7	0,306 51
0,219	0,584 7	0,310 04
0,220	0,584 7	0,313 59
0,221	0,584 7	0,317 17
0,222	0,584 7	0,320 77
0,223	0,584 7	0,324 39
0,224	0,584 7	0,328 03
0,225	0,584 6	0,331 68
0,226	0,584 6	0,335 35
0,227	0,584 6	0,339 07
0,228	0,584 6	0,342 82
0,229	0,584 6	0,346 59
0,230	0,584 6	0,350 39
0,231	0,584 6	0,354 21
0,232	0,584 6	0,358 06
0,233	0,584 6	0,361 93
0,234	0,584 6	0,365 82
0,235	0,584 6	0,369 74
0,236	0,584 6	0,373 69
0,237	0,584 6	0,377 66
0,238	0,584 6	0,381 66
0,239	0,584 6	0,385 68
0,240	0,584 6	0,389 73
0,241	0,584 6	0,393 80
0,242	0,584 6	0,397 90
0,243	0,584 6	0,402 02
0,244	0,584 6	0,406 17

Table E.1 (*continued*)

Head h m	Coefficient C_d	Discharge Q $m^3/s \times 10^{-1}$
0,245	0,584 6	0,410 34
0,246	0,584 6	0,414 54
0,247	0,584 6	0,418 77
0,248	0,584 6	0,423 02
0,249	0,584 6	0,427 30
0,250	0,584 6	0,431 60
0,251	0,584 6	0,435 93
0,252	0,584 6	0,440 28
0,253	0,584 6	0,440 66
0,254	0,584 6	0,449 07
0,255	0,584 6	0,453 50
0,256	0,584 6	0,457 96
0,257	0,584 6	0,462 45
0,258	0,584 6	0,466 96
0,259	0,584 6	0,471 50
0,260	0,584 6	0,476 06
0,261	0,584 6	0,480 65
0,262	0,584 6	0,485 27
0,263	0,584 6	0,489 91
0,264	0,584 6	0,494 58
0,265	0,584 6	0,499 28
0,266	0,584 6	0,404 00
0,267	0,584 6	0,508 76
0,268	0,584 6	0,513 53
0,269	0,584 6	0,518 34
0,270	0,584 6	0,523 17
0,271	0,584 6	0,528 02
0,272	0,584 6	0,532 91
0,273	0,584 6	0,537 82
0,274	0,584 6	0,542 76
0,275	0,584 6	0,547 72
0,276	0,584 6	0,552 72
0,277	0,584 6	0,557 74
0,278	0,584 6	0,562 82
0,279	0,584 7	0,567 94

Head h m	Coefficient C_d	Discharge Q $m^3/s \times 10^{-1}$
0,280	0,584 7	0,573 06
0,281	0,584 7	0,578 19
0,282	0,584 7	0,583 35
0,283	0,584 7	0,588 53
0,284	0,584 7	0,593 75
0,285	0,584 7	0,598 99
0,286	0,584 7	0,604 25
0,287	0,584 7	0,609 55
0,288	0,584 7	0,614 87
0,289	0,584 7	0,620 23
0,290	0,584 7	0,625 60
0,291	0,584 7	0,631 01
0,292	0,584 7	0,636 45
0,293	0,584 7	0,664 95
0,294	0,584 8	0,647 48
0,295	0,584 8	0,653 03
0,296	0,584 8	0,658 58
0,297	0,584 8	0,664 16
0,298	0,584 8	0,669 76
0,299	0,584 8	0,675 39
0,300	0,584 8	0,681 06
0,301	0,584 8	0,686 75
0,302	0,584 8	0,692 46
0,303	0,584 8	0,698 21`
0,304	0,584 8	0,703 98
0,305	0,584 8	0,709 80
0,306	0,584 8	0,715 68
0,307	0,584 9	0,721 59
0,308	0,584 9	0,727 50
0,309	0,584 9	0,733 41
0,310	0,584 9	0,739 36
0,311	0,584 9	0,745 34
0,312	0,584 9	0,751 35
0,313	0,584 9	0,757 38
0,314	0,584 9	0,763 44