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Hydrometric determinations — Flow measurements in open channels using structures — Use of vertical underflow gates

Déterminations hydrométriques — Mesure de débit dans les canaux découverts au moyen de structures — Emploi de portes verticales à passage subaquatique

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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 International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13550 was prepared by Technical Committee ISO/TC 113, *Hydrometric determinations*, Subcommittee SC 2, *Notches, weirs and flumes*.

Hydrometric determinations — Flow measurements in open channels using structures — Use of vertical underflow gates

1 Scope

This International Standard specifies methods for the determination of discharge in open channels in steady flow conditions using vertical underflow gates on a flat horizontal floor between vertical side walls under modular or non-modular conditions.

NOTE Generally, gate controls are not designed with discharge determination as a primary function and this International Standard is intended to help the development of stage-discharge relations at existing gate structures, and to incorporate into new structures features which will provide good facilities for the establishment of stage-discharge relations.

When a better accuracy of measurement (i.e. better than specified in 9.4) is required, the structure is to be calibrated with actual measurement of discharge using an appropriate method.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 772, *Hydrometric determinations — Vocabulary and symbols*

ISO 4373, *Measurement of liquid flow in open channels — Water-level measuring devices*

ISO/TR 5168, *Measurement of fluid flow — Evaluation of uncertainties*

3 Terms, definitions and symbols

For the purposes of this International Standard, the terms, definitions and symbols given in ISO 772 apply together with the following.

3.1
vertical underflow gate
vertical gate situated in a channel of rectangular cross-section with a flat bottom for regulating the water level upstream of the gate or the discharge through the gate opening

NOTE 1 The gate is movable in vertical slots and it can be raised or lowered by hand or mechanically.

NOTE 2 The underflow is two-dimensional except at vertically narrow gate openings.

4 Units of measurement

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

5 General requirements

5.1 General

Conditions regarding preliminary survey, selection of site, approach channel, installation and maintenance of structures, gauge wells and measurement of head which are generally necessary for flow measurement are given in 5.2 and 5.3. The operational requirements for vertical underflow gates are given separately in 8.5.

5.2 Site selection

A preliminary survey 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 the discharge determination using gates.

Particular attention shall be paid to the following features:

a) existence of an adequate length of channel of regular cross-section;

b) flow velocity distribution;

c) absence of a steep channel, if possible;

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

e) sediment content of the stream and possibility of deposition of floating debris just upstream of the gate, affecting its performance;

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

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

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

i) removal of rocks or boulders from the bed of the approach channel;

j) effects of wind, which can have a considerable effect on the flow in a river or under a gate, especially when the channel is wide and the head is small, and when the prevailing wind is in a transverse direction;

k) in a natural channel, the necessity or otherwise to provide facilities for the passage of fish.

If the site does not possess the characteristics necessary for satisfactory measurement, the site shall be rejected unless suitable improvements are practicable.

If an inspection of the stream shows that the existing velocity distribution is regular, then it may be assumed that the velocity distribution will remain satisfactory after the construction of the gate.

If the existing velocity distribution is irregular and no other site for a gauge is feasible, the distribution shall be checked after the installation of the gate and improved if necessary.

Several methods are available for obtaining a more precise indication of irregular velocity distribution. Velocity rods, floats or concentrations of dye can be used in small channels, the latter being useful in checking conditions at the bottom of the channel. A complete and quantitative assessment of velocity distribution may be made using a current meter. Further information on the use of current meters is given in ISO 748.

5.3 Installation conditions

5.3.1 General

The complete measuring installation consists of an approach channel, a measuring structure and a downstream channel. The condition of each of these components affects the overall accuracy of the measurements.

Installation parameters include such features as gate finish, cross-sectional shape of channel, channel roughness and the influence of the control section of devices upstream or downstream of the gauging structure.

The distribution and direction of velocity have an important influence on the performance of a gate, which is determined by the features mentioned above.

Once an installation has been designed and constructed, the user shall avoid any change which could affect the discharge characteristics.

5.3.2 Approach channel

On all installations the flow in the approach channel shall be smooth, free from disturbance and shall have a velocity distribution as normal as possible over the cross-sectional area. These criteria can usually be verified by inspection or measurement. In the case of natural streams or rivers, they can only be met by a long straight approach channel free from projections either at the side or on the bed. Unless otherwise specified in the appropriate clauses, the approach channel shall comply with the following general requirements.

The change in flow conditions due to construction of the gate may cause build-up of floating debris upstream of the structure, which in time might affect the flow conditions.

In an artificial channel, the cross-section shall be uniform and the channel shall be straight for a length equal to at least five times its width measured from the upstream side of the abutments.

If entry of the approach channel is through a bend or if the flow is discharged into the channel through a conduit of smaller cross-section, or at an angle, then a greater length of straight approach channel will be required to achieve a regular velocity distribution. Baffles in the approach channel shall not be closer to the point of measurement than a distance of 10 times the maximum head to be measured.

Under certain conditions, a standing wave may occur upstream of the gauging device, for example if the approach channel is steep. Provided this wave is at a distance of not less than 30 times the maximum head upstream, flow measurement will be feasible, subject to confirmation that a regular velocity distribution exists at the approach to the weir. If a standing wave occurs within this distance, the approach conditions and/or the gauging device shall be modified.

5.3.3 Measuring structure

The structure shall be rigid, watertight and capable of withstanding flood flow conditions without displacement, distortion or fracture. It shall be at right angles to the direction of flow and shall conform to the dimensions given in the relevant clauses.

The surface of the sill and the side walls of the channel in which the gate is located shall be smooth, particularly in the section from some distance upstream to some distance downstream of the gate.

The bottom, sill and side walls may be constructed of concrete with a smooth cement finish.

The lower edge of the gate shall be horizontal, regular in shape and straight.

The construction shall satisfy the following tolerances:

- on the width of the channel (b) in which the gate is located: 0,5 % of the width;
- on point deviations from a plane surface of the flat bottom: 0,2 % of b, with an absolute maximum of 0,01 m;
- on point deviations from a horizontal plane of the lower edge of the gate: 0,2 % of b, with an absolute maximum of 0,01 m.

5.3.4 Downstream of the structure

The channel downstream of the structure is usually of no importance if the weir has been designed to operate under modular conditions. However, if the weir is designed to measure the flow under non-modular conditions, the downstream channel shall be straight for a length of at least eight times the maximum head to be measured. In that case, the flow shall be subcritical at the downstream face of the gate.

A downstream gauge shall be provided to obtain the submergence ratio. An additional gauge located a short distance just downstream of the gate is recommended to check the existence of modular or non-modular flow.

6 Maintenance

Maintenance of the measuring structure and the approach channel is an important factor for accurate continuous measurements.

It is essential that the approach channel to the gates and the channel downstream of the gates be kept clean and free from silt and vegetation as far as is practicable for at least the distances specified in 5.3.2 and 5.3.4. The float well and the entry from the approach channel shall also be kept clean and free from deposits. The gate structure shall be kept clean and free from clinging or floating debris, and care shall be taken during cleaning to avoid damage to the gate.

7 Measurement of head

7.1 General

The heads upstream and downstream of the measuring structure may be measured by a hook gauge, point gauge or staff gauge where spot measurements are required, or by a float-operated recording gauge or presssure-sensing gauge where a continuous record is required. It is preferable to measure heads in a separate stilling well to reduce the effects of water surface irregularities. Other head measuring methods may be used provided that a measurement accuracy of ± 5 mm is obtainable.

A gauge or other measuring device is needed to measure the opening of the gate with respect to the sill of the gate. The accuracy shall be of the same order as that for the head measurement devices.

If very hot or very cold conditions prevail, causing a significant temperature difference between the liquid in a stilling well and the liquid in a channel, a correction for differences in liquid density may have to be made in the calculation of rates of discharge.

7.2 Stilling or float well

The stilling well should be vertical and have sufficient length so that, at the maximum water level estimated to be recorded in the well, the counterweight will not rest on top of the float or be submerged. An additional margin of 0,6 m is recommended.

The well shall be connected to the channel by an inlet pipe or slot, large enough to permit the water in the well to follow the rise and fall of head without significant delay. The connecting pipe or slot shall, however, be as small as possible consistent with ease of maintenance, or shall alternatively be fitted with a constriction to damp out oscillations due to short-period waves. In general, the diameter of the intake pipe will not be smaller than 0,1 times the diameter of the well.

The well and the connecting pipe or slot shall be watertight. Where accommodation of the float of a water level recorder is provided for, the well shall be of adequate diameter and depth to accommodate the float. The well shall also be deep enough to accommodate any sediment which may enter, without the float grounding. The float well arrangement may include an intermediate chamber between the stilling well and the approach channel, of similar proportions to the stilling well to enable sediment to settle.

Specifications for stilling wells are given in ISO 4373.

7.3 Zero setting

A means of checking the zero settings of the head measuring devices shall be provided, consisting of a pointer or staff gauge, set at a fixed level with respect to the sill of the gate and fixed permanently in the approach or downstream channel, separate from the stilling well or float well. Benchmarks, related to a National Datum to facilitate their relationship to the topography of the channel basin, should be established nearby and settings of the gauges checked annually by levels.

The opening of the gate also varies. The elevation of the lower crest of the gate with respect to the sill of the gate can be read from a fixed gauge. A typical method for measuring the elevation of a vertical gate is by installation of this gauge, fixed at the abutment and parallel to the gate, on which a horizontal strip indicates the elevation of the gate. Gate openings can be recorded by gearing a recorder to a cable attached to the gate or the gate gears or shafts.

8 Vertical underflow gates

8.1 Description of vertical underflow gates

Gated structures with undershot flow are used as head regulators and as offtakes. Vertical gates are raised and lowered in vertical slots which are constructed in the vertical abutments and intermediate piers (see Figure 1). In this way discharges can be regulated and measured.

It is strongly recommended that intake structures be designed in such a way that only one type of flow will occur (modular flow or submerged flow) so as to prevent discontinuities during operation. This shall be achieved by selecting the bottom elevation of the sluice gate sufficiently high (for free flow) or low (for submerged flow) with relation to the downstream water level.

The discharge through vertical slide gates may be determined by measuring the gate opening a, the upstream and downstream water levels h_1 and h_2 and by applying the correct discharge equation for modular flow or submerged flow.

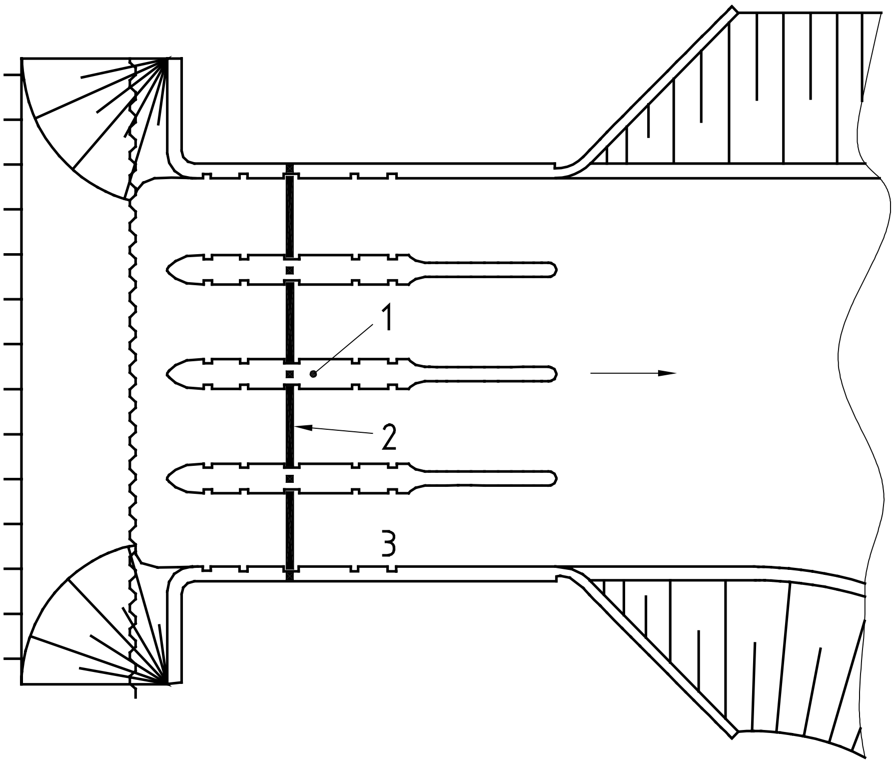
All discharge equations given in 9.1 are based on two-dimensional flow. Therefore the gates are operated in a rectangular section formed by vertical walls and a level horizontal floor. In the case of two-dimensional flow, the upstream and downstream water levels shall be measured in the rectangular section between the abutments and intermediate piers, for each gate separately.

In many field structures, however, the upstream and downstream water levels are measured at one location upstream of the upstream face and downstream of the downstream face of the abutments and piers. The effect of additional losses is defined in 9.2 (three-dimensional gate flow).

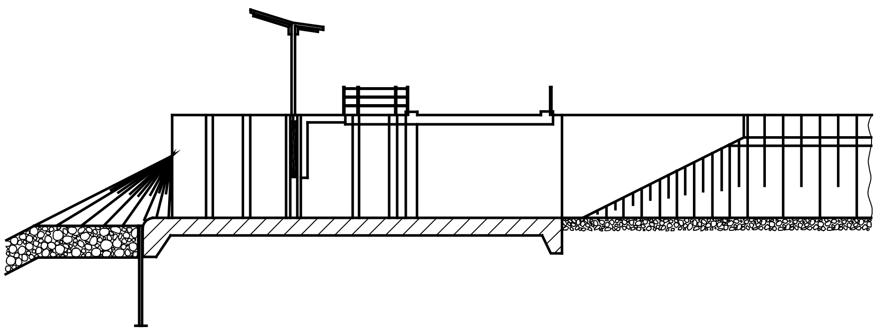
The general layout of a structure with vertical underflow gates is given in Figure 1.

A sketch of the bottom of the gate is given in Figure 2.

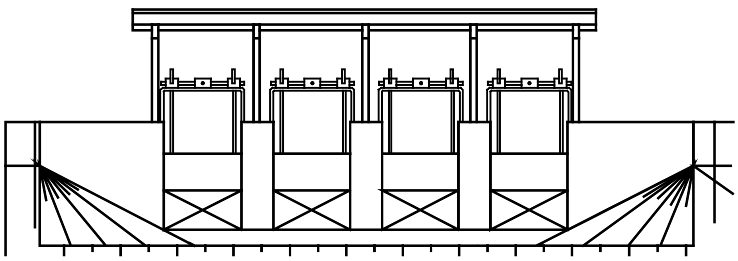
The radius r of the circular rounding of the bottom edge may vary as follows: $0 \leqslant r \leqslant e$.



a) Plan



b) Longitudinal section



c) Upstream view

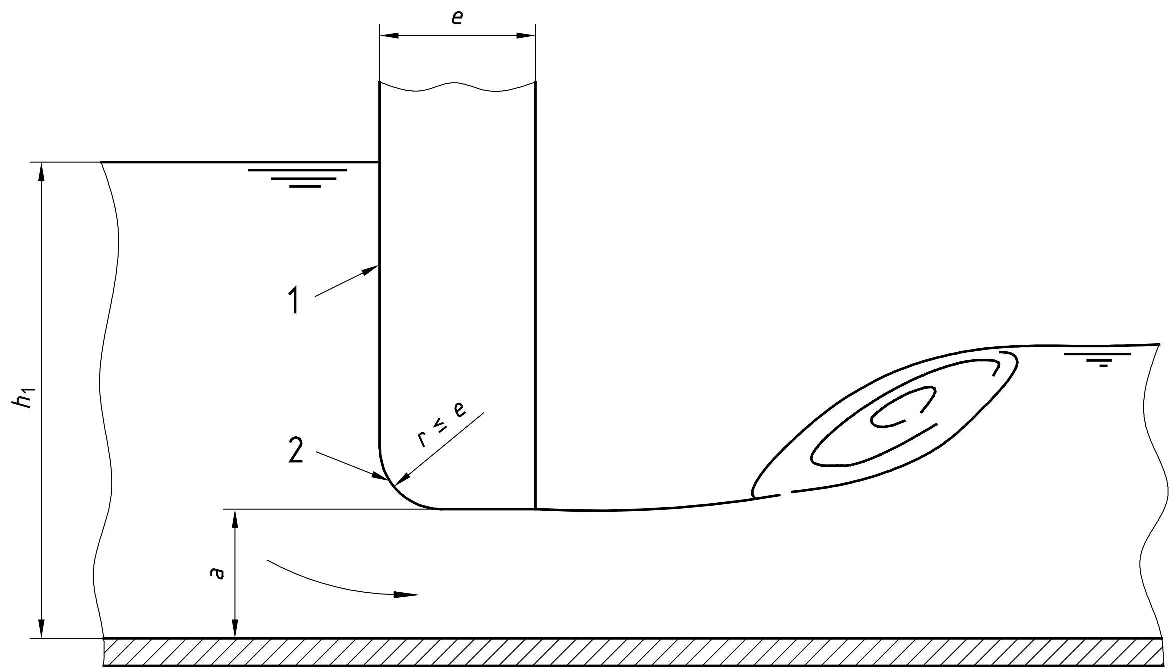
Key

1 Pier

2 Gate

3 Abutment

Figure 1 — Gated intake structure



Key

1 Upstream face

2 Bottom edge

Figure 2 — Bottom edge of a gate

8.2 Location of the head measurement section

The water level gauging station upstream of the gate shall be located at a sufficient distance upstream from the gate to avoid the region of eddies. On the other hand, it shall be close enough to the gate to ensure that the energy loss between the section of measurement and the control section under the gate is negligible. It is recommended that the head-measurement section be located upstream from the gate at a distance not exceeding twice the maximum head over the gate.

8.3 Location of the tailwater level measurement section

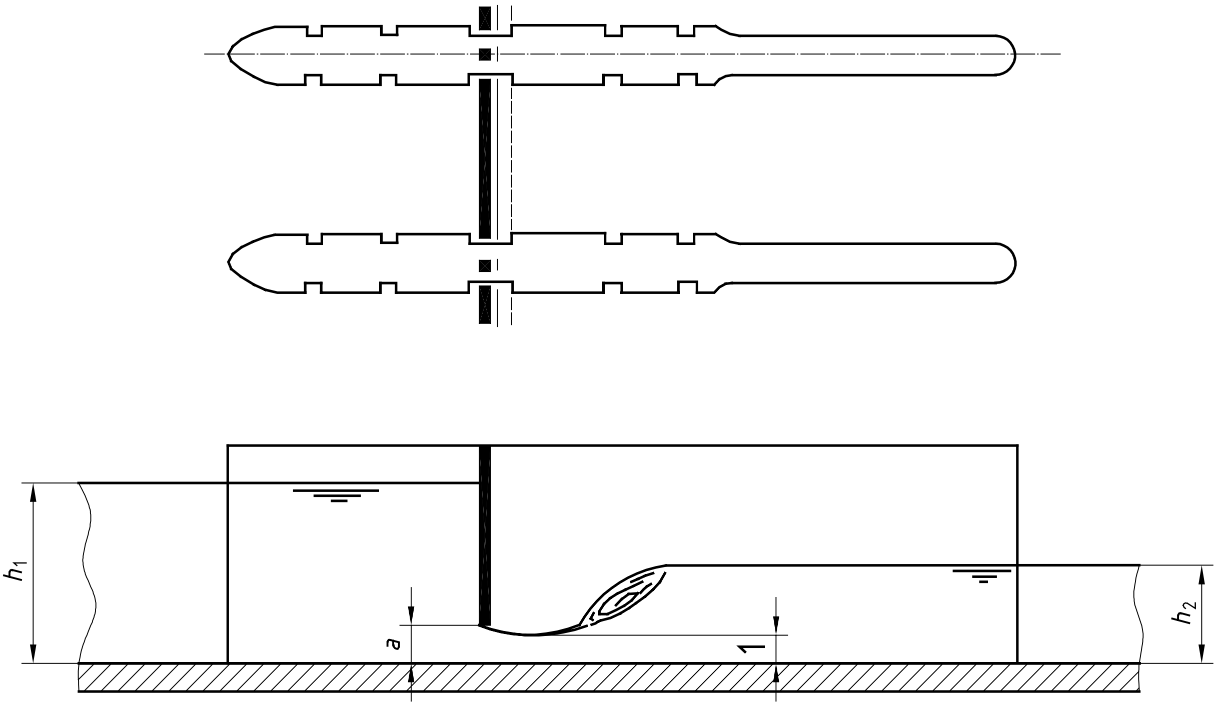
The water-level gauging station downstream of the gate used to measure the downstream head in the case of submerged flow shall be located at a sufficient distance downstream from the gate to avoid regions of fluctuations. Generally, it is recommended that the tailwater level measurement section be located at a distance of 10 times the tailwater depth downstream from the gate, so that the measurement is free of unstable water surface.

An additional water-level gauging station, to check if modular or submerged flow exists, shall be located as close to the gate as possible.

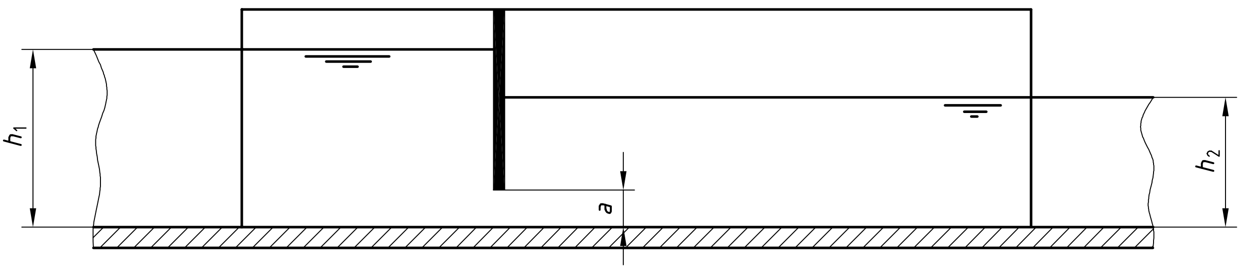
8.4 Flow types

The discharge capacity of any structure is governed by the shape and dimensions of its control section and by the head losses upstream and downstream of this section.

For a gated intake structure, the control section is defined by the “vena contracta” which is the minimum cross section at a short distance downstream of the gate (see Figure 3). Contraction of streamlines in the vertical direction predominates.



a) Modular gate flow



b) Submerged gate flow

Key

1 Vena contracta

Figure 3 — Different flow types in a gated structure

Depending on the interrelation between the parameters h_1, h_2 and a, the following flow types (indicated in Figure 3) can occur in a gated structure.

a) **Modular gate flow** (referred to also as free flow): The contraction of streamlines towards the gate opening is strong in the vertical plane. The higher the h_1/a value (see Figure 4) the stronger is the curvature of streamlines and the lower the discharge coefficient C_D. C_D is a function of C_C, a and h_1, where C_C is the contraction coefficient. For modular flow, the downstream water level is low enough so that the capacity of the structure will not be affected. A free jet leaves from the gate opening, and a hydraulic jump is located at some distance downstream of the gate. The discharge Q is as follows:

$$Q = f(h_1, a, C_C)$$

b) **Submerged gate flow**: Now the roller of the hydraulic jump has submerged the free jet. The discharge Q is as follows:

$Q = f(h_1, h_2, a \text{ and } C_C)$

There is a fairly sharp limit between modular and submerged gate flow, which can be seen by observing the location of the hydraulic jump. This limit can be calculated from the parameters h_1/a, h_2/a and C_C.

8.5 Operational requirements and recommendations

The following operational requirements shall be followed, and recommendations considered.

a) The shape of the upstream bottom edge shall be well defined, so as to determine the correct value of the contraction coefficient C_C.

b) The bottom of the undershot gate shall be truly horizontal.

c) For accurate discharge measurements, the structure shall be equipped with water level recorders upstream and downstream of a gate or the structure as described in 8.2 and 8.3, and with a device indicating the gate opening. The location of the intake to the stilling wells should be in such a way that the measured head shall not be affected by high turbulence or other irregularities of the water surface, or by drawdown or build-up caused by improper orientation. Generally the opening will be flush with the wall.

d) For structures with two or more gates, it is recommended that all the gates be operated under exactly the same opening height for the following reasons:

   1) different heights can result in angular flow when flow passes in front of gates with small openings towards gates with large openings; this makes determination of the total discharge complicated and less accurate;

   2) by using all the gates at the same opening, the velocity distribution over the full width of the channel is more uniform, upstream as well as downstream of the structure, resulting in lower maximum flow velocities.

e) The rounding, R, of abutments and piers shall be at least $R = b/8$ for moderate approach velocities and $R = b/4$ for high velocities, to prevent additional losses due to contraction and expansion (b is the width of one opening).

9 Discharge relationships

9.1 Discharge equations and coefficients for two-dimensional flow

9.1.1 Modular flow

Figure 4 shows underflow through a vertical gate.

The discharge equation for modular flow is as follows:

$$Q = C_D ab\sqrt{2gh_1} \qquad (1)$$

where

Q is the discharge, in cubic metres per second;

C_D is the discharge coefficient

a is the height of gate opening, in metres;

b is the width of the gate opening, in metres;

g is the acceleration due to gravity (9,81 m/s^2);

h_1 is the upstream water level, related to the sill level, in metres.

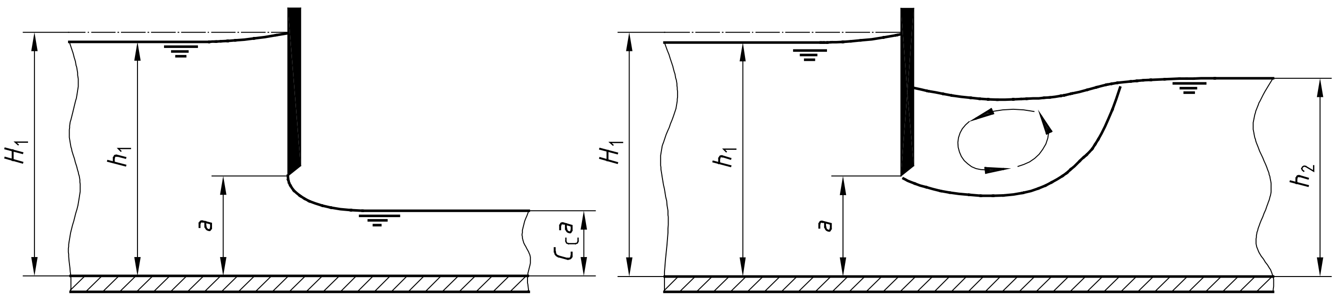


Figure 4 — Underflow through a vertical gate

The discharge coefficient is defined as follows:

$$C_D = \frac{C_C}{\sqrt{1 + \frac{C_C\, a}{h_1}}} \tag{2}$$

where C_C is the contraction coefficient of the jet, which depends mainly on the shape of the bottom edge:

$$C_C = 0{,}510 + 0{,}1\sqrt{23{,}04 - (2r/a - 4{,}69)^2} \text{ for } r/a < 2{,}35 \text{ and} \tag{3}$$

$$C_C = 0{,}990 \text{ for } r/a \geqslant 2{,}35$$

and r is the radius of the circular rounding of the bottom edge.

NOTE Equation (3) is based on laboratory measurements.

Figure 5 gives the contraction coefficient as a function of r/a.

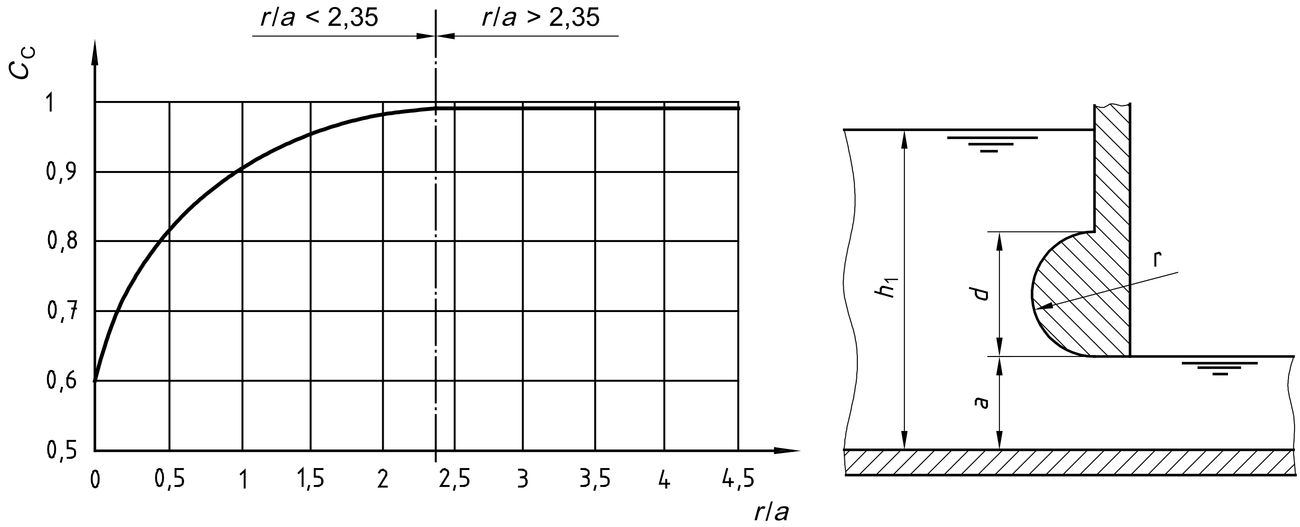


Figure 5 — Contraction coefficient C_C as a function of r/a

9.1.2 Limit between modular flow and submerged flow

Modular flow turns into submerged flow, or conversely, at the so-called modular limit for which the equation is related to the contraction coefficient C_C, H_1 and a, as shown by the equation:

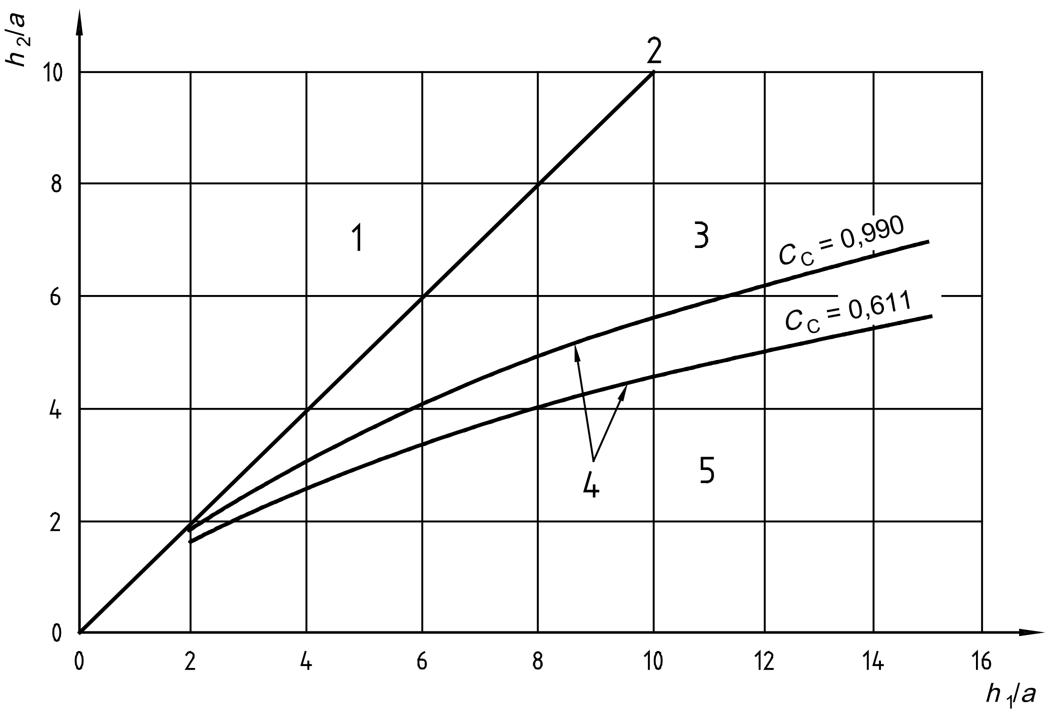
$$\frac{h_2}{a} = \frac{C_C}{2}\left[\sqrt{1+16\left(\frac{H_1}{aC_C}-1\right)}-1\right] \quad (4)$$

where

h_2 is the downstream water level, related to the sill level, in metres;

H_1 is the upstream energy head, related to the sill level, in metres.

Taking $H_1 = h_1$, values of h_2/a can be calculated for any C_C value, provided that two-dimensional flow occurs. Figure 6 shows the modular limits for a sharp bottom edge, C_C = 0,611 and a well-rounded bottom edge, C_C = 0,990. Apparently well-rounded gates allow a higher downstream water level than sharp-edged gates.



Key

1 Backflow

2 No flow

3 Submerged flow

4 Modular limits

5 Modular flow

Figure 6 — Limit between free flow and submerged flow

9.1.3 Submerged flow

The discharge equation is as follows:

$$Q = C_{dr} C_D \, ab \sqrt{2 g h_1} \tag{5}$$

where

C_D is the discharge coefficient for modular flow (9.1.1);

C_{dr} is the coefficient of submergence, $C_{dr} = f\left(h_1/a, h_2/a, C_C\right)$.

Figure 7 shows C_{dr} values for a sharp-edged gate C_C = 0,611 and a well rounded gate C_C = 0,990.

The C_{dr} coefficient is defined as follows:

$$C_{dr} = \sqrt{\frac{1 - \frac{2\alpha}{1-\alpha^2}(1-\beta) - \sqrt{\left(\frac{2\alpha}{1-\alpha^2}(1-\beta)-1\right)^2 + \frac{\alpha^2}{\beta^2} - 1}}{1-\alpha}} \tag{6}$$

where

$$\alpha = \frac{aC_C}{h_1} \text{ and } \beta = \frac{aC_C}{h_2} \tag{7}$$

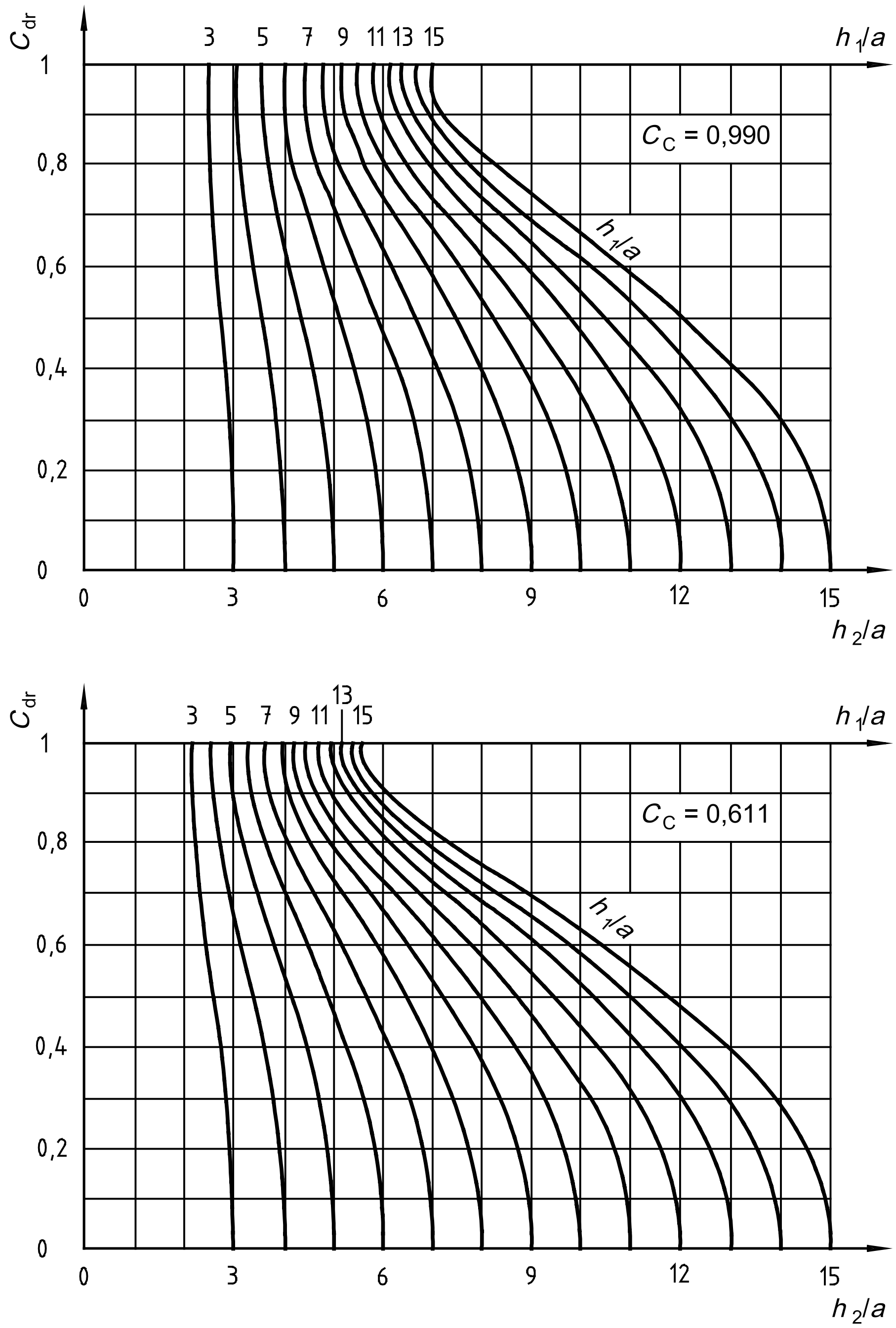


Figure 7 — Coefficient C_{dr} for submerged flow

9.2 Three-dimensional gate flow

Head regulators and other gated intake structures provided with vertical slide gates are hydraulic structures usually having a number of gates which are operated in the rectangular sections formed by the weir abutments and intermediate piers.

In most structures the length of the vertical walls of the abutments and piers is relatively short. As a consequence, the flow conditions in the rectangular sections do not allow two-dimensional flow. In practice, the water levels h_1 and h_2 will often not be measured in the section between the abutments upstream and downstream of one gate, but are measured in sections upstream (h'_1) and downstream (h'_2) of the total structure.

Figure 8 is a definition sketch of the total loss of head for three-dimensional gate flow.

In general terms, the total loss of head over the intake structure can be expressed as follows:

$$h'_1 - h'_2 = (h'_1 - h_1) + (h_1 - h_2) + (h_2 - h'_2) \quad (8)$$

where the partial losses are as follows.

a) Entrance:

$$h'_1 - h_1 = (1 + \xi_i)(v_1^2 / 2g) - ({v'_1}^2 / 2g) \quad (9)$$

where ξ_i is the entrance loss coefficient.

b) Gate:

$$h_1 - h_2 \quad (10)$$

which is assumed to be the head loss due to two-dimensional gate flow.

c) Exit:

$$h_2 - h'_2 = ({v'_2}^2 / 2g) + (\xi_o - 1)(v_2^2 / 2g) \quad (11)$$

where ξ_o is the exit loss coefficient.

The rating curve for three-dimensional gate flow can now be computed from information about the loss coefficients ξ_i and ξ_o and from the characteristics of the two-dimensional flow.

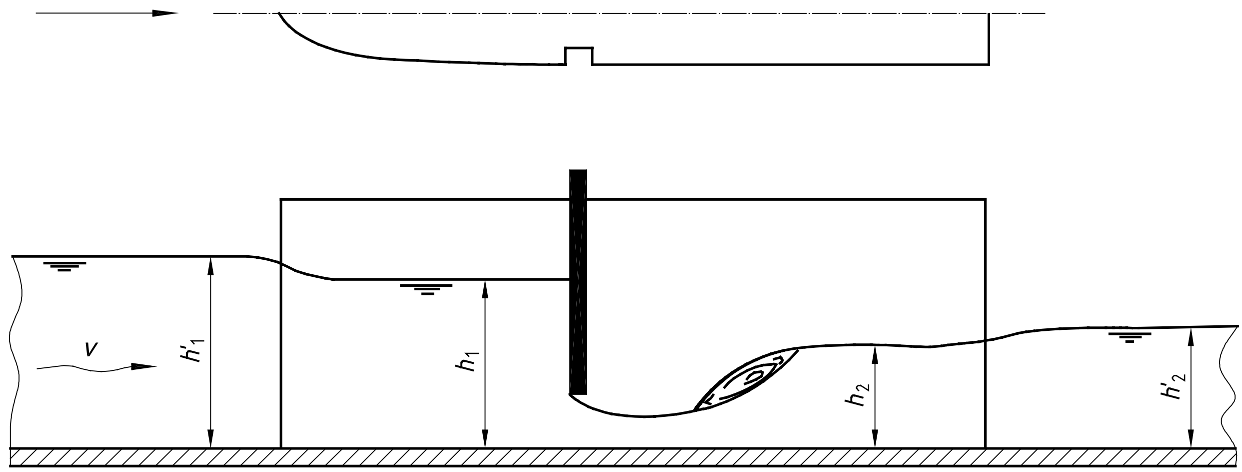


Figure 8 — Loss of head for three-dimensional flow

The computed relation may deviate from the real situation because of one or more of the following uncertainties:

— description of the bottom-edge rounding, r (inaccurate C_C value);

— inaccuracy of the estimated ξ_i and ξ_o values;

— interaction between the different losses: entrance, gate and exit.

Calibration of the structure in the field or by a hydraulic model study may lead to a more accurate rating curve.

9.3 Limits of application

To prevent air-entraining vortices immediately upstream of the gate, the gate opening shall be such that $h_1/a \geqslant 2$.

To prevent three-dimensional flow in the case of a vertically narrow gate opening, h_1/b shall be < 3 (b is the width of one opening).

9.4 Uncertainty of measurement

The overall uncertainty of flow measurements made with vertical underflow gates depends on the uncertainties of head measurements h_1 and h_2, of the measurement of the gate opening a and of the coefficients C_D and C_{dr} as they apply to the gate in use.

With reasonable care and skill in the construction, installation and operation of a vertical underflow gate, the systematic uncertainty in the coefficient C_D will be within 5 %.

For submerged flow the uncertainty in C_{dr} increases as the differential head $h_1 - h_2$ decreases. The systematic uncertainty in the coefficient C_{dr} will be as follows:

— 6 % for $h_1/a \geqslant 5$;

— from 6 % to 12 % for $2 < h_1/a < 5$.

At very small differences of $h_1 - h_2$, the uncertainty can increase considerably.

The random uncertainty in the coefficient C_D and C_{dr} reflects the real but marginal changes in the coefficient values during changing discharge, and may be taken as 1,0 %.

The method by which the uncertainties in the coefficients shall be combined with other sources of uncertainty is given in clause 10.

The total uncertainty in the discharge through gated structures, derived from measurements of h_1, h_2 and a, is expected to range between 10 % and 20 %:

— two-dimensional modular flow: < 10 %

— two-dimensional submerged flow: 10 % to 15 %

— three-dimensional flow: 10 % to 20 %

9.5 Example of computation

9.5.1 General

The following subclauses give examples of the computation of discharge under modular flow and submerged flow conditions using a vertical gate above a flat bottom (two-dimensional flow) with the following dimensions:

— $r = 0$ (sharp bottom edge);

— $b = 6{,}00$ m;

— opening $a = 0{,}40$ m.

9.5.2 Modular flow

Consider the following values:

— head h_1 = 2,00 m, head h_2 = 1,00 m

— C_C for a sharp bottom edge = 0,611

Therefore:

— h_1/a = 2,00/0,40 = 5

— h_2/a = 1,00/0,40 = 2,5

Figure 6 shows that modular flow will exist, or using equation (4) the modular limit for h_2/a is

$$\frac{h_2}{a} = \frac{0,611}{2} \times \left[\sqrt{1 + 16\left(\frac{2,00}{0,40 \times 0,611} - 1 \right)} - 1 \right] = 2,98$$

This confirms that modular flow will exist.

The discharge coefficient from equation (2) is

$$C_D = \frac{0,611}{\sqrt{1 + \frac{0,611 \times 0,40}{2,00}}} = 0,577$$

The discharge is then by equation (1)

$$Q = 0,577 \times 0,40 \times 6,00 \times \sqrt{2 \times 9,81 \times 2,00} = 8,67 \text{m}^3\text{/s}$$

9.5.3 Submerged flow

If head h_1 = 2,00 m, head h_2 = 1,60 m:

— h_1/a = 2,00/0,40 = 5

— h_2/a = 1,60/0,40 = 4

Both from Figure 6 and equation (4), it is clear that submerged flow will exist.

From Figure 7 (for C_C = 0,611) C_{dr} is found to be about 0,56.

Or using equations (6) and (7)

$$\alpha = \frac{0,40 \times 0,611}{2,00} = 0,122$$

$$\beta = \frac{0,40 \times 0,611}{1,60} = 0,153$$

$$C_{dr} = \sqrt{\frac{1 - \frac{2 \times 0{,}122}{1 - 0{,}122^2}(1 - 0{,}153) - \sqrt{\left(\frac{2 \times 0{,}122}{1 - 0{,}122^2}(1 - 0{,}153) - 1\right)^2 + \frac{0{,}122^2}{0{,}153^2} - 1}}{1 - 0{,}122}} = 0{,}565$$

Then, from equation (5), the discharge is

$$Q = 0{,}565 \times 0{,}577 \times 0{,}40 \times 6{,}00 \times \sqrt{2 \times 9{,}81 \times 2{,}00} = 4{,}90 \text{ m}^3/\text{s}$$

10 Uncertainties in flow measurement

10.1 General

Reference shall also be made to ISO/TR 5168.

Whenever a measurement of discharge is made, the value obtained is simply the best possible estimate of the true discharge. In practice, the true discharge may be slightly greater or less than this value. This International Standard gives the procedure for the evaluation of uncertainties in individual flow measurements arising from both random and systematic errors.

The error is the difference between the true rate of flow and that calculated in accordance with the equation for the gate, which is assumed to be constructed and installed in accordance with this International Standard. The term "uncertainty" is used to denote the deviation from the true rate of flow within which the measurement is expected to lie 19 times out of 20 (95 % confidence level).

The total uncertainty of any flow measurement can be estimated if the uncertainties from various sources are combined. As the discharge is obtained as a function of gate dimensions, measuring head and discharge coefficients, errors in these quantities contribute to the total uncertainty in discharge measurement. The assessment of these contributions to the total uncertainty will indicate whether or not the rate of flow can be determined with sufficient accuracy for the purpose in hand.

10.2 Sources of error

The sources of error in discharge measurement may be identified by considering a generalized form of the discharge equation for a vertical gate:

$$Q = C_{dr} C_D ab\sqrt{2gh_1} \tag{12}$$

where g is the acceleration due to gravity, which varies from place to place, but in general the variation is small enough to be neglected in flow measurements.

Thus only the following sources of error need to be considered:

a) the discharge coefficient C_D and the submerged flow coefficient C_{dr}; numerical estimates of the uncertainty in these coefficients are given in 9.4;

b) the dimensions of the structure, i.e. the width of the gate b and the gate opening a;

c) the measured heads h_1 and h_2.

The uncertainties in a, b, h_1 and h_2 need to be estimated by the user. The uncertainty in dimensional measurement will depend upon the accuracy to which the device, as constructed, can measure; in practice this uncertainty can prove to be insignificant in comparison with other uncertainties. The uncertainty in the head will depend upon the accuracy of the head measuring device, the determination of the gauge zero and the technique used. The uncertainty can be small if a vernier or micrometer instrument is used, with a zero determination of comparable precision.

10.3 Kinds of error

Errors can be classified as random errors and systematic errors. Random errors are caused by numerous small independent influences which prevent a measurement system from delivering the same reading from the same input value of the quantity being measured. The random error in the result can be reduced by making a number of measurements and using the arithmetic mean value.

The standard deviation is used as a measure of the random error. The standard deviation of a set of measurements under steady conditions may be estimated from the equation:

$$s_y = \left[\frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-1} \right]^{1/2} \quad (13)$$

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

The standard deviation of the mean is then given by

$$s_{\bar{y}} = \frac{s_y}{\sqrt{n}} \quad (14)$$

The uncertainty of the mean at the 95 % confidence level is given by $t_{95} s_{\bar{y}}$. This uncertainty is the contribution of random errors in any series of experimental measurements to the total uncertainty. The value of t_{95} is 2,0 for $n \geqslant 30$. It is 2,6 for n = 6; 2,4 for n = 8; 2,3 for n = 10; and 2,1 for n = 15.

Systematic errors are those which cannot be reduced by increasing the number of measurements if the equipment and conditions of measurement remain unchanged. For example, an error in setting the zero of a water-level gauge to crest level produces a systematic difference between the measurement head and the actual value. The uncertainty associated with systematic errors cannot be assessed experimentally without changing the equipment or conditions of measurement. Generally, as subjective judgement is involved in the estimation of systematic uncertainty, the stated level of 95 % has to be treated as approximate for systematic errors.

10.4 Uncertainties

10.4.1 Uncertainties in values of coefficients C_D and C_{dr}

All errors in this category are systematic.

The values of the coefficients C_D and C_{dr} quoted in this International Standard are based on experiments which can 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 can occur, which may be attributed to variations in the surface finish of the device, its installation, the approach conditions, the scale effect between model and site structure, etc.

The uncertainty in the coefficients quoted in the preceding clauses are based on a consideration of the deviation of experimental data from various sources from the correlation given. The suggested uncertainty values thus represent an accumulation of the evidence and experience available.

10.4.2 Uncertainties in measurements made by the users

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

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

The uncertainty of the gauged head shall be determined from an assessment of the individual sources of error (e.g. zero error, gauge sensitivity, backlash in the indication mechanism, or residual random uncertainty in the mean of a series of measurements). The uncertainty of the gauged head is the square root of the sum of the squares of the individual uncertainties.

10.4.3 Combination of uncertainties

The total random or systematic uncertainty is the resultant of several contributory uncertainties, which can 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.

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

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

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

$$X'_Q = \sqrt{(X'_{C_\mathrm{D}})^2 + (X'_{C_\mathrm{dr}})^2 + (X'_a)^2 + (X'_b)^2 + (0{,}5X'_{h_1})^2} \qquad (15)$$

where

X'_{C_D} is the percentage random uncertainty in C_D;

X'_{C_dr} is the percentage random uncertainty in C_dr;

X'_a is the percentage random uncertainty in a;

X'_b is the percentage random uncertainty in b;

X'_{h_1} is the percentage random uncertainty in h_1.

The random uncertainties in C_D and C_dr are given in 9.4. The random uncertainties in b and h_1 can be obtained as stated in 10.3 by obtaining estimates of the standard deviation. The standard deviation is easily estimated if, for example, a graduated rod is used for head measurement. For continuous or digital recording equipment, the random uncertainty in reading a given water level may be assessed by laboratory tests on the equipment.

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

$$X''_Q = \sqrt{(X''_{C_\mathrm{D}})^2 + (X''_{C_\mathrm{dr}})^2 + (X''_a)^2 + (X''_b)^2 + (0{,}5X''_{h_1})^2} \qquad (16)$$

where

X''_{C_D} is the percentage systematic uncertainty in C_D;

$X''_{C_{dr}}$ is the percentage systematic uncertainty in C_{dr};

X''_a is the percentage systematic uncertainty in a;

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

X''_{h_1} is the percentage systematic uncertainty in h_1.

To obtain estimates of systematic uncertainties in a, b and h_1, see ISO 5168. The systematic uncertainties in C_D and C_{dr} are given in 9.4.

It should be noted that the uncertainty in the rate of flow is not a single value for a given gate, but varies with flow. It may therefore be necessary to consider the uncertainties at several rates of flow covering the required range of measurement and flow conditions (i.e. modular or non-modular).

10.5 Presentation of results

Although it is preferable to list systematic and random uncertainties separately, there are many practical reasons for presenting a single combined value of the total uncertainty. For this reason, the systematic and random uncertainties may be combined by the root-sum-square method.

In the presentation of results, the random error and systematic error should be indicated separately, as well as the combined uncertainty.

10.6 Examples

The following are examples of the computation of the discharge and associated uncertainty in a single measurement of flow, using a vertical undershot gate for modular flow conditions and for submerged flow conditions through one single gate.

The dimensions of the gate are as follows:

- bottom-edge rounding r = 0,05 m
- gate opening a = 0,80 m
- gate width b = 2,50 m (identical to the width between the abutments)

a) Modular flow

The gauged heads are as follows:

- upstream h_1 = 3,20 m
- downstream h_2 = 1,60 m

For calculation of the discharge, the equations in 9.1.1 are used.

The contraction coefficient C_C is calculated from equation (3) with the data:

a = 0,80 m and r = 0,05 m; C_C = 0,658

The discharge coefficient C_D is calculated from equation (2) with the data:

a = 0,80 m, h_1 = 3,20 m and C_C = 0,658; C_D = 0,610

The discharge using equation (1) in 9.1.1 is:

$$Q = 0{,}610 \times 0{,}80 \times 2{,}50 \times \sqrt{2 \times 9{,}81 \times 3{,}20} = 9{,}67 \text{ m}^3/\text{s}$$

The random and systematic uncertainties in the value of C_D are obtained from 9.4 as:

$$X'_{C_D} = 1{,}0\ \%$$

$$X''_{C_D} = 5{,}0\ \%$$

Assuming that the mean of several measurements is used for width b, the random uncertainty in b is likely to be negligible. The systematic uncertainty in the width measurement is estimated to be 0,025 m. Accordingly:

$$X'_b = 0$$

$$X''_b = \frac{0{,}025}{2{,}5} \times 100 = 1{,}0\ \%$$

Likewise, the uncertainties in the measurement of the gate opening a are estimated as follows with a systematic uncertainty in the gate opening of 0,005 m. Accordingly:

$$X'_a = 0$$

$$X''_a = \frac{0{,}005}{0{,}80} \times 100 = 0{,}63\ \%$$

The random uncertainty in the measurement of head may be determined by taking a series of readings at a given water level. The random uncertainty at the specified head is estimated as 5 mm for the equipment used. For the equipment used and the conditions of measurement, which includes error in zero setting, the systematic uncertainty is estimated as 10 mm. Accordingly:

$$X'_h = \frac{0{,}005}{3{,}20} \times 100 = 0{,}16\ \%$$

$$X''_h = \frac{0{,}010}{3{,}20} \times 100 = 0{,}31\ \%$$

The combination of individual uncertainties to obtain the uncertainty in discharge is carried out as follows.

The random uncertainty in discharge is given by equation (15) in 10.4.3 as:

$$X'_Q = \sqrt{(1{,}0)^2 + (0{,}5 \times 0{,}16)^2} = 1{,}00\ \%$$

The systematic uncertainty in discharge is given by equation (16) in 10.4.3 as:

$$X''_Q = \sqrt{(5{,}0)^2 + (0{,}63)^2 + (1{,}0)^2 + (0{,}5 \times 0{,}31)^2} = 5{,}14\ \%$$

Combining the random and systematic uncertainties by the root-sum-square method yields:

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

$$= \sqrt{(1{,}00)^2 + (5{,}14)^2} = 5{,}24\ \%$$

The discharge Q may be described as follows:

— discharge Q = 9,67 m^3/s

— random uncertainty $X'_Q = 1{,}00\ \%$

— systematic uncertainty $X''_Q = 5{,}14\ \%$

— combined uncertainty $X_Q = 5{,}24\ \%$

Finally it is checked that flow is modular, using equation (4) in 9.1.2.

The data used in the example are: H_1 = 3,20 m, a = 0,80 m and C_C = 0,658. The downstream head h_2 = 1,60 m. The modular limit is h_2/0,80 = 2,655 or h_2 = 2,124 m. The measured downstream head is 0,524 m below the modular limit.

b) Submerged flow

The gauged heads are as follows:

— upstream h_1 = 3,20 m

— downstream h_2 = 2,75 m

For calculation of the discharge, the equations in 9.1.3 are used.

The discharge coefficient C_D = 0,610 (identical to the value in a) above.

The coefficient of submergence C_{dr} is calculated using equation (6) with

$$\alpha = \frac{0{,}80 \times 0{,}658}{3{,}20} = 0{,}164\ 5$$

$$\beta = \frac{0{,}80 \times 0{,}658}{2{,}75} = 0{,}191\ 4$$

Therefore, C_{dr} = 0,502.

The discharge calculated using equation (5) is

$$Q = 0{,}502 \times 0{,}610 \times 0{,}80 \times 2{,}50 \times \sqrt{2 \times 9{,}81 \times 3{,}20} = 4{,}85\ m^3/s$$

The random and systematic uncertainties in the coefficients are

$X'_{C_D} = 1{,}0\ \%$ $\quad X'_{C_{dr}} = 1{,}0\ \%$

$X''_{C_D} = 5{,}0\ \%$ $\quad X''_{C_{dr}} = 10{,}0\ \%$ $\quad (h_1/a = 4)$

The uncertainties in a and b are identical to those given in a) above:

$X'_a = 0$ $\quad X'_b = 0$

$X''_a = 0{,}63\ \%$ $\quad X''_b = 1{,}0\ \%$

The uncertainties in head measurement are taken from a) above:

$X'_h = 0{,}16\ \%$

$X''_h = 0{,}31\ \%$

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

The random uncertainty in discharge is given by equation (15) in 10.4.3 as

$$X'_Q = \sqrt{(1{,}0)^2 + (1{,}0)^2 + (0{,}5 \times 0{,}16)^2} = 1{,}42\ \%$$

The systematic uncertainty in discharge is given by equation (16) in 10.4.3 as

$$X''_Q = \sqrt{(5{,}0)^2 + (10{,}0)^2 + (0{,}63)^2 + (1{,}0)^2 + (0{,}5 \times 0{,}31)^2} = 11{,}24\ \%$$

Combining the random and systematic uncertainties by the root-sum-square method yields

$$X_Q = \sqrt{(X'_Q)^2 + (X''_Q)^2} = \sqrt{(1{,}42)^2 + (11{,}24)^2} = 11{,}33\ \%$$

The discharge Q may be described as follows:

— discharge $Q = 4{,}85\ m^3/s$

— random uncertainty $X'_Q = 1{,}42\ \%$

— systematic uncertainty $X''_Q = 11{,}24\ \%$

— combined uncertainty $X_Q = 11{,}33\ \%$

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