International Standard 4359

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Liquid flow measurement in open channels — Rectangular, trapezoidal and U-shaped flumes

Mesure de débit des liquides dans les canaux découverts — Canaux jaugeurs à col rectangulaire, à col trapézoïdal et à col en U

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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 developing International Standards is carried out through ISO technical committees. Every member body interested in a subject for which a technical committee has been authorized 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.

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

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

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France
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India
Ireland
Italy
Netherlands
Spain
Switzerland
USA

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Belgium
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Annexes

Liquid flow measurement in open channels — Rectangular, trapezoidal and U-shaped flumes

1 Scope and field of application

This International Standard deals with the measurement of flow in rivers and artificial channels under steady or slowly varying flow conditions, using certain types of standing-wave (or critical depth) flumes. A wide variety of flumes has been designed but only those which have received general acceptance after adequate research and field testing, and which therefore do not require *in-situ* calibration are considered. Three types of flumes, covering a wide range of applications are recommended as follows :

a) Rectangular-throated (see figure 1).

b) Trapezoidal-throated (see figure 4).

c) U-throated, i.e. round-bottomed (see figure 5).

The flow conditions considered are uniquely dependent on the upstream head, i.e. subcritical flow must exist upstream of the flume, after which the flow accelerates through the contraction and passes through its critical depth, and the water level beyond the structure is low enough to have no influence upon its performance.

Annex A gives the guidelines for the selection of weirs and flumes for the measurement of the discharge of water in open channels.

2 References

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

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

ISO 1438, *Liquid flow measurement in open channels using thin-plate weirs and venturi flumes.*

3 Definitions and symbols

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

4 Units of measurement

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

5 Selection of the type of flume

5.1 The type of flume that should be used depends upon several factors, such as the range of discharge to be measured, the accuracy required, the head available and whether or not the flow carries sediment.

5.2 The rectangular-throated flume is simpler to construct. To achieve proportionality, i.e. to avoid either ponding or drawdown in the approach channel when the discharge is variable, provision of a hump in the bed becomes necessary with discharges bigger or smaller than the design discharge (see figure 2).

5.3 The trapezoidal-throated flume is more appropriate where a wide range of discharge is to be measured with consistent accuracy. This shape of throat is particularly suitable where it is necessary to work to a given stage-discharge relationship.

5.4 The U-throated flume is useful for installation in a U-shaped channel or where discharge is from a circular-section conduit. It has found particular application in sewers and at sewage works.

6 Installation

6.1 Selection of site

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

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

a) The adequacy of the length of channel of regular cross-section available.

b) The uniformity of the existing velocity distribution (see annex C).

c) The avoidance of a steep channel (but see 6.2.2).

d) The effects of any increased upstream water levels due to the measuring structure.

e) The conditions downstream (including such influences as tides, confluences with other streams, sluice gates, mill dams and other controlling features, including seasonal weed growth, which might cause drowning).

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

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

h) The stability of the banks, and the necessity for trimming and/or revetment.

j) Uniformity of the section of the approach channel.

k) Effect of wind, which can have a considerable effect on the flow over a river, weir or flume, especially when these are wide and the head is small and when the prevailing wind is in a transverse direction.

m) Aquatic weed growth.

n) Sediment transportation.

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

6.2 Installation conditions

6.2.1 General requirements

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

6.2.1.2 The distribution and direction of velocity may have an important influence on the performance of a flume (see 6.2.2 and annex C).

6.2.1.3 Once a flume has been installed, any changes in the system which affect the basis of the design will change the discharge characteristics.

6.2.2 Approach channel

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

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

6.2.2.3 The length of uniform approach channel suggested in 6.2.2.2 refers to the distance upstream of the head measuring position. However, in a natural channel it would be uneconomic to line the bed and banks with concrete for this distance, and it would be necessary to provide a contraction in plan if the width of the lined approach to the flume throat is less than the width of the natural channel. The unlined channel upstream of the contraction shall nevertheless comply with the requirements of 6.2.2.1 and 6.2.2.2.

6.2.2.4 Wing walls to effect a contraction in plan shall be symmetrically disposed with respect to the centre line of the channel and should preferably be curved with a radius not less than $2H_{max}$. The downstream tangent point shall be at least H_{max} upstream of the head measurement section, and the lined section of approach channel from the end of the curved wing walls to the entrance transition of the flume shall be of prismatic section.

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

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

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

6.3 Flume structure

6.3.1 The structure shall be rigid and watertight and capable of withstanding flood flow conditions without damage from outflanking or from downstream erosion. The axis shall be in line with the direction of flow of the upstream channel, and the geometry shall conform to the dimensions given in the relevant clauses.

6.3.2 The surfaces of the flume throat and the immediate approach channel shall be smooth : they can be constructed in concrete with a smooth cement finish or surfaced with a smooth non-corrodible material. In laboratory installations, the finish shall be equivalent to rolled sheet metal or planed, sanded and painted timber. The surface finish is of particular importance within the prismatic part of the throat but can be relaxed a distance along the profile $0{,}5H_{max}$ upstream and downstream of the throat proper.

6.3.3 In order to minimise uncertainty in the discharge, the following tolerances are acceptable :

a) On the bottom width of the throat, 0,2 % of this width with an absolute maximum of 0,01 m.

b) On deviation from a plane of the plane surfaces in the throat, 0,1 % of L.

c) On the width between vertical surfaces in the throat, 0,2 % of this width with a maximum of 0,01 m.

d) On the average longitudinal and transverse slopes of the base of the throat 0,1 %.

e) On a slope of inclined surfaces in the throat, 0,1 %.

f) On a length of the throat, 1 % of L.

g) On deviation from a cylindrical or a conical surface in the entrance transition to the throat, 0,1 % of L.

h) On deviation from a plane of the plane surfaces in the entrance transition to the throat, 0,1 % of L.

j) On deviation from a plane of the plane surfaces in the exit transition from the throat, 0,3 % of L.

k) On other vertical or inclined surfaces, deviation from a plane or curve, 1 %.

m) On deviation from a plane of the bed of the lined approach channel, 0,1 % of L.

The structure shall be measured on completion, and average values of relevant dimensions and their standard deviations at 95 % confidence limits computed. The former shall be used for computation of discharge and the latter shall be used to obtain the overall uncertainty in the determination of discharge (see 13.5).

6.4 Downstream conditions

The flow conditions downstream of the structure are important in that they control the tail water level which may influence the operation of the flume. The flume shall be so designed that it cannot become drowned under the operating conditions (see 10.3.1, 11.3.2 and 12.3.2). Construction of a flume in a river or stream may alter flow conditions and cause scouring downstream of the structure. This may result in accumulation of river bed material further downstream which, in time, may raise the normal water level sufficiently to drown the flume, particularly at low rates of flow. Any such accumulation of material shall be removed before it becomes excessive.

7 Maintenance — General requirements

Maintenance of the measuring structure and the approach channel is important to secure accurate continuous measurements.

It is essential that the approach channel to flumes shall be kept clean and free from silt and vegetation as far as practicable for at least the distance specified in 6.2.2.2. The float-well, and the entry from the approach channel shall also be kept clean and free from deposits.

The throat and the curved entry to a flume shall be kept clean and free from algal growths.

8 Measurement of head

8.1 General requirements

8.1.1 Where spot measurements are required, the head upstream of the flume throat can be measured by a vertical or inclined gauge, a hook, point, wire or tape gauge. Where a continuous record is required, a recording gauge shall be used. The location of the head measurement section is dealt with in 10.2, 11.2 and 12.2.

8.1.2 As the size of the flume and the head on it reduces, small errors in construction and in the zero setting and reading of the head measuring device become of greater relative importance.

8.2 Gauge well

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

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

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

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

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

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

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

8.3 Zero setting

8.3.1 Initial setting of the zero of the head-measuring device accurately with reference to the level of the invert of the throat, and regular checking of this setting thereafter, is essential if overall accuracy is to be attained.

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

9 Determination of discharge

9.1 General equations for discharge

9.1.1 Critical depth theory, augmented by experimental data, may be used to deduce the basic equations for free discharge through a streamlined contraction. The simple theory relates to the frictionless flow of an ideal fluid, and an additional coefficient has to be introduced in practice, either based on experiment or deduced by considering a modification to the simple theory, taking account of the boundary layer development with a real fluid such as water. This International Standard describes desk calculating methods for determining discharge but where many structures are being considered, computer analysis may be more appropriate.

9.1.2 The specific energy, E, of flow in an open channel is given by :

$$E = \beta d + \alpha \bar{v}^2/2g \qquad \ldots (1)$$

where

d is the depth of flow;

$\bar{v}$ is the average velocity through the section;

α is the coefficient taking into account non-uniformity in velocity distribution;

β is the coefficient dependent on the mean curvature of the streamlines.

The equation of continuity is :

$$Q = A\bar{v} \qquad \ldots (2)$$

where

Q is the total discharge;

A is the area of the flow cross-section.

Hence

$$E = \beta d + \alpha Q^2/2g\,A^2 \qquad \ldots (3)$$

Critical flow occurs when E has its minimum value for a given discharge Q, treating the depth d, and the area A which is related to it for any given cross-section geometry, as the variables. It can be shown that the specific energy is a minimum when

$$Q^2 = \frac{\beta g\,A^3}{\alpha w} \qquad \ldots (4)$$

where w is the water surface width.

9.1.3 Experimentally observed velocity profiles indicate that the velocity distribution is almost uniform in the throat of a flume, and it may be assumed therefore that $\alpha = 1$. If the streamlines are not significantly curved, a condition approached if the throat is in excess of a certain minimum length, then $\beta = 1$. Hence the basic equation defining critical flow through a streamlined contraction is

$$Q = (g\,A_c^3/w_c)^{1/2} \qquad \ldots (5)$$

the subscript c indicating critical flow.

9.1.4 Equation (5) is not immediately applicable to the theoretical derivation of a stage-discharge relationship, because :

a) it does not take account of the development of a boundary layer of slower moving fluid in the throat;

b) it is based on the area and water surface width at the critical section, the location of which is ill-defined so that direct measurement of the water level at that section is impractical.

Thus the basic equation has to be transformed into a more practical form, and adjusted to take account of the boundary effects.

9.2 Calculation of discharge from observed head

9.2.1 For the flow of a real fluid through a streamlined rectangular contraction, equation (5) can be expressed in terms of the effective total head as follows :

$$Q = \left(\frac{2}{3}\right)^{3/2} b_e \sqrt{g}\,H_e^{3/2} \qquad \ldots (6)$$

where

b_e is the effective width of flume throat;

H_e is the effective total head.

9.2.2 Equation (6) can then be expressed in terms of h_e, the effective head gauged upstream of the structure, for flumes with rectangular throats as follows :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g}\,C_v\,b_e\,h_e^{3/2} \qquad \ldots (7)$$

where

$$C_v = (H_e/h_e)^{3/2} \qquad \ldots (8)$$

C_v is a dimensionless coefficient allowing for the effect of approach velocity on the measured water level upstream of the weir. Effective heads and widths can be determined from observed values

a) by a simple empirical correction (see 10.4.1, 11.4.1 and 12.4.1), or

b) by theoretical considerations of boundary layer development (see annex D).

9.2.3 Analogous relationships can be derived for flumes with trapezoidal throats :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g}\,C_v\,C_s\,b_e\,h_e^{3/2} \qquad \ldots (9)$$

where

C_s is a numerical coefficient which takes into account the non-rectangular flow section.

$$C_s = f(m\,H_{ce}/b_e) \qquad \ldots (10)$$

H_{ce} is the effective total head at critical section.

Although theoretical design and calibration procedures exist utilizing the above equations, they are cumbersome. This is largely because C_s is dependent on H_{ce} which differs significantly from the gauged head h. An alternative method of computing discharge from equation (5) is given in 11.5.

9.2.4 The corresponding relationship for U-throated flumes is :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g}\,C_v\,C_u\,D_e\,h_e^{3/2} \qquad \ldots (11)$$

where

C_u is a numerical constant which takes account of the non-rectangular flow section.

$$C_u = f(H_{ce}/D_e) \qquad \ldots (12)$$

D_e is the effective diameter of base of the U-shaped throat.

9.3 Calculation of stage-discharge relationships

9.3.1 In the case of a flume with a rectangular throat equation (7) has to be used to compute the stage-discharge relationship for the structure. However, equations (9) and (11) cannot conveniently be used to compute this relationship for trapezoidal and U-throated flumes. An alternative approach can be used.

9.3.2 A theoretical calibration for a gauging structure for the whole range of discharge can be derived by considering flow conditions in the throat of the flume and deducing corresponding heads and discharges. The principle of the method is to select a series of values of d_c the critical depth in the throat, and calculate corresponding values of Q and H_e using the expressions

$$Q = (g\,A_c^3/w_c)^{1/2} \qquad \ldots (13)$$

and

$$H_e = d_c + \frac{A_c}{2w_c} \qquad \ldots (14)$$

The effective total head, H_e, can be converted to total head, H, as described in 11.5 and 12.5 and total head H, can be converted to measured gauged head, h, as outlined in 11.5 and 12.5.

9.4 Approach velocity

9.4.1 The total head is related to the gauged head by the equation :

$$H_e = h_e + \alpha\bar{v}_a^2/2g \qquad \ldots (15)$$

where

$\bar{v}_a$ is the mean velocity in the approach channel at the gauging section;

α is a coefficient (the kinetic energy or Coriolis coefficient) which takes account of the fact that the kinetic energy head exceeds $\bar{v}_a^2/2g$ if the velocity distribution across the section is not uniform.

In applying the equations in this International Standard, α may be taken as unity, with the tolerances given in 10.7.2, 11.8.2 and 12.7.2 and the provisions of 6.2.2 and bearing in mind annex C.

9.4.2 From equations (8) and (15), coupled with equations (7), (9) and (11), a general relationship for C_v may be defined by :

$$(C_v^{2/3} - 1)^{1/2} = \frac{2}{3\sqrt{3}} \times \frac{b_e\,h_e}{A}\,C_v\,C_{s\text{ or }u} \qquad \ldots (16)$$

where A is the cross-sectional area of the approach channel flow.

9.4.3 For a rectangular approach channel

$$A = B(h + p) \qquad \ldots (17)$$

where

B is the width of the approach channel;

p is the height of flume invert above the invert of the approach channel.

9.4.4 For a trapezoidal approach channel :

$$A = (h + p)\,[B + m_a(h + p)] \qquad \ldots (18)$$

where

B relates to the bed width of the approach channel;

m_a is the side slope of the approach channel walls.

9.4.5 For a U-shaped approach channel :

$$A = \frac{\pi}{4}\,D_a^2\,f\,[(h + p)/D_a] \qquad \ldots (19)$$

where D_a is the diametrical width of the approach channel.

10 Rectangular throated flume

10.1 Description

10.1.1 The rectangular throated flume consists of a constriction of rectangular cross-section symmetrically disposed with respect to the approach channel.

This is the most common type of flume and the easiest to construct, but it cannot be adapted to suit non-rectangular channels when loss of head is important.

10.1.2 There are three types of rectangular throated flumes :

a) with side contractions only;

b) with bottom contraction or hump only;

c) with both side and bottom contractions.

The type to be used depends on downstream conditions at various rates of flow, the maximum rate of flow, the permissible head loss and the limitations of the h/b ratio, and whether or not the stream carries sediment.

10.1.3 The invert of the throat shall be level throughout its width and length. The sides of the flume throat shall be vertical and parallel and square with the invert, so that the width of the throat is accurate from top to bottom and end to end. The surfaces of the throat and entrance transition shall be smooth; they may be constructed in concrete with a smooth finish, or lined with a smooth non-corrodible material. The centre line of the throat shall be in line with the centre line of the approach channel. In the case of flumes without a hump (bottom contraction), the floor of the approach channel shall be level, and at no point higher than the invert of the throat, for a distance of at least $2h_{max}$ upstream of the head measurement section.

10.1.4 The flume geometry shall be as shown in figure 1. The radius of the curved transition to the bed and walls of the throat shall be at least $4p$ and $2(B - b)$ respectively. The 1 in 6 expansion beyond the throat may be truncated as shown in figure 1 when recovery of head is not important.

10.1.5 When the required recovery of head is more than 80 %, the alternative flume geometry with side and bottom contractions could be as shown in figure 2. The glacis slope downstream of the throat shall be 1 in 20 for a length of $2H$ (where H is the total head above the sill of the hump) beyond which it may be more. The length of the side walls downstream of throat shall be $4H$ and their divergence shall be 1 in 10. For greater recovery of heads, the side walls shall be parallel up to the toe of the glacis and then a hyperbolic expansion should be given up to the pont where the downstream channel begins.

NOTE — When the ratio of the depth of water downstream above the sill of the throat to depth of water upstream over the sill of the throat is less than 0,5, a flumed standing wave fall (see figure 3) should be used with baffle platform, baffle wall, stilling basin and deflectors for efficient dissipation of energy.

10.2 Location of head measurement section

The head on the flume shall be measured at a point far enough upstream of the contraction to be clear of the effects of draw-down, but close enough to ensure that the energy loss between the section of measurement and the throat will be negligible. It is recommended that the head measurement section be located a distance of between 3 and 4 times h_{max} upstream of the leading edge of the entrance transition.

10.3 Provision for modular flow

10.3.1 Flow is modular when it is independent of variations in tail-water level, and for this to be so, the velocity has to be the critical velocity in the throat. The invert level shall therefore be at such an elevation as to produce modular flow for the full range of design discharges. The dimensions of the flume shall be such that the total head upstream (relative to throat invert) is at least 1,25 times that downstream (assuming subcritical flow exists downstream) at all rates of flow. Nevertheless, it may be possible to reduce this difference provided that the occurrence of free discharge is confirmed. On the other hand, if the expansion is truncated, the ratio shall be at least 1,33.

10.3.2 In artificial channels it is frequently possible to determine the depth downstream at various rates of flow with reasonable accuracy, for example by means of a friction formula if the channel is long enough and of constant slope or by reference to the characteristics of controlling features downstream.

If the flume is to be installed in an existing channel or stream the following information should then be obtained at the site :

a) The maximum depth recorded with an estimate of the rate of flow at that depth.

b) The approximate depths at two or more intermediate rates of flow.

c) The dead water level in the stream, i.e. the level under zero flow conditions.

10.4 Evaluation of discharge

10.4.1 The basic discharge equation for rectangular throated flumes is given in 9.2.2 and this may be rewritten as :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g}\, C_{\text{v}}\, C_{\text{D}}\, b\, h^{3/2} \qquad \ldots (20)$$

where

$$C_{\text{D}} = \left(\frac{b_{\text{e}}}{b}\right)\left(\frac{h_{\text{e}}}{h}\right)^{3/2} \qquad \ldots (21)$$

but

$$b_{\text{e}} = b - 2\delta_* \qquad \ldots (22)$$

$$h_{\text{e}} = h - \delta_* \qquad \ldots (23)$$

where δ_* is the boundary layer displacement thickness.

Substituting from (22) to (23) into (21)

$$C_{\text{D}} = \left(1 - 2\frac{\delta_*}{L} \times \frac{L}{b}\right)\left(1 - \frac{\delta_*}{L} \times \frac{L}{h}\right)^{3/2} \qquad \ldots (24)$$

where L is the length of prismatic section of the contraction at the flume.

For most installations with a good surface finish the value of δ_*/L will, in practice, lie in the range 0,002 to 0,004. Provided $10^5 > L/k_{\text{s}} > 4\,000$ and $Re > 2 \times 10^5$, δ_*/L may be assumed equal to 0,003.

Equation (24) then becomes :

$$C_{\text{D}} = \left(1 - \frac{0{,}006\, L}{b}\right)\left(1 - \frac{0{,}003\, L}{h}\right)^{3/2} \qquad \ldots (25)$$

Various values of C_{D} derived from this equation are given in table 1 and these are the values which apply to well-constructed installations as detailed above.

10.4.2 A more sophisticated approach is given in annex D which takes into account the development of the boundary layer in the throat of the flume. This enables the user to take into account the variability of δ_*/L and to use the more general expression for C_{D} given in equation (24).

10.4.3 The value of C_{v} can be computed from equations (16), (17), (22) and (23), or more conveniently, can be read from figure 6 or extracted from table 2 to a sufficiently close approximation. Figure 6 is expressed in terms of b_{e}, h_{e} and A, but in practice it will be found acceptable to use B and h in place of b_{e} and h_{e} in entering the diagram. Table 2 implicitly makes this assumption. In cases where the approach channel is not truly rectangular in section where h is measured, B can be determined from the expression :

$$B = \frac{\text{Cross-sectional area}}{h + p} \qquad \ldots (26)$$

10.4.4 The procedure indicated in 10.4.3 shall be adopted for calibration. For *preliminary* design purposes, however, in the case of the flume shown in figure 2, the discharge equation can be expressed as :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g}\, C\, b\, H^{3/2} \qquad \ldots (27)$$

where C is the overall coefficient and for design purposes may be assumed to have a value between 0,97 and 1,00.

When the structure is combined with a bridge having piers in the throat, the term b in equation (27) can be replaced by

$$(b - n_p b_p - 2C_c n_p H)$$

where

b_p is the width of pier;

n_p is the number of piers;

C_c is the coefficient of contraction
= 0,045 for piers with round nose
= 0,040 for piers with pointed nose.

10.5 Computation of stage-discharge relationship

10.5.1 The stage-discharge relationship for a rectangular throated flume is obtained by considering a series of values of gauged head, h, and repeating the method given in 10.4.1 to 10.4.3 for each. Corresponding gauged heads and discharges can then be plotted to provide the stage-discharge relationship for the flume.

10.6 Limits of application

10.6.1 The practical lower limit of h is related to the magnitude of the influence of fluid properties and boundary roughness. The recommended lower limit of 0,05 m or 0,05L, whichever is the greater.

10.6.2 There is also a limit on the ratio of the areas of the approach channel and the throat arising from difficulties experienced when the Froude number in the approach channel exceeds 0,5. The recommended upper limit of

$$\frac{bh}{B(h + p)}$$

is 0,7.

10.6.3 Other limitations arise from inadequate experimental confirmation for extreme sizes or geometries :

a) b shall be not less than 0,10 m.

b) h/b shall be not more than 3.

c) h shall be not more than 2 m.

10.6.4 h/L should not exceed 0,50. This limitation on h/L arises from the necessity to ensure parallel flow conditions at the critical section in the throat. h_{max}/L may be allowed to rise to 0,67, with an additional uncertainty in coefficient of 2 %.

10.7 Uncertainty of measurement

10.7.1 The overall uncertainty of measurement will depend on :

a) the standard of construction and finish of the flume;

b) the uncertainty of the formula for the coefficient of discharge;

c) the uncertainty of the velocity of approach coefficient;

d) a correct application of the installation conditions;

e) the uncertainty of the zero setting;

f) the uncertainty of measurement of the geometry of the flume;

g) the accuracy of the head gauge.

10.7.2 With reasonable skill and care in the construction of the flume, the coefficients are expected to have an uncertainty approaching 1 % in favourable circumstances, for example when C_D and C_v are not far from unity. An estimate of the combined percentage uncertainty (X_C) on the coefficients may be obtained from the equation :

$$X_C = \pm [1 + 20 (C_v - C_D)] \qquad \ldots (28)$$

10.7.3 The method by which the uncertainty of the coefficients is to be combined with the uncertainties due to other sources of error is explained in clause 13. [In applying equation (28), C_D is obtained from equation (25).]

11 Trapezoidal throated flumes

11.1 Description

11.1.1 Trapezoidal throated flumes can be designed to cope with many different flow conditions, and the optimum throat geometry (i.e. bed width and side slopes) will depend on the range of flow to be measured and on the characteristics of the stream or channel in which it is to be installed. Design methods by which the geometry might be selected to approximate to an existing or predetermined stage-discharge relation are outlined in 11.6.

11.1.2 Trapezoidal throated flumes should have a geometry generally as indicated in figure 4. In some circumstances, however, it will be appropriate to make the invert of the throat level with the invert of the approach channel, i.e. $p = 0$; this will be the case if sediment has to be conveyed through the flume. This International Standard covers only that class of trapezoidal throated flume in which the sloping walls of the throat extend above water level.

11.1.3 The flume shall be installed with the throat centre line in line with the centre of the approach channel. Subcritical flow shall exist in the flume approach, and the flume shall be installed at such an elevation as to operate with free discharge throughout the range. The surfaces of the flume shall be of smooth concrete, galvanized steel or other smooth non-corrodible material. The throat section is of particular importance and shall have a level invert and be truly prismatic, the sloping walls being plane surfaces, symmetrically disposed and making a sharp intersection with the invert of the throat.

11.1.4 The entrance and exit transitions may be plane or curved surfaces to suit convenience of construction.

11.1.5 The convergence of the entrance transition on any plane section, if formed from plane surfaces, should not be more than 1 in 3 at each side. If curved surfaces are used, these shall be well-streamlined, for example by using the face of inclined cylinders, or a skew cylinder, or a vertical-axis cone. The surfaces shall lie entirely inside (i.e. on the channel centre-line side of) planes defining a 1 in 3 convergence on each side, and if curved shall terminate truly tangential to the planes forming the throat.

11.1.6 The surfaces forming the exit transition shall lie entirely inside planes defining a 1 in 3 expansion on each side. A 1 in 6 expansion gives very good recovery of head and a high modular limit.

11.2 Location of head measurement section

The head on the flume shall be measured at a point far enough upstream of the contraction to be clear of the effects of draw-down, but close enough to ensure that the energy loss between the section of measurement and the throat will be negligible. It is recommended that the head measurement section should be located a distance of between 3 and 4 times $h_{\max}$ upstream of the leading edge of the entrance transition.

11.3 Provision for modular flow

11.3.1 Flow is modular when it is independent of variations in tail-water level, and for this to be so, the velocity shall pass through the critical velocity in the throat. The invert level shall therefore be at such an elevation as to produce modular flow for the full range of design discharges. The dimensions of the flume shall be such that the total head upstream is well in excess of that downstream when related to the invert of the throat (assuming subcritical flow exists downstream).

11.3.2 As the modular limit is dependent on head recovery beyond the throat, the necessary ratio of upstream to downstream head is dependent on the angle of expansion, as follows :

1 in 20 each side	$H/H_d \geqslant 1{,}10$
1 in 10 each side	$H/H_d \geqslant 1{,}20$
1 in 6 each side	$H/H_d \geqslant 1{,}25$
1 in 3 each side	$H/H_d \geqslant 1{,}35$

where H_d is the total head just beyond the exit transition, related to the flume invert.

11.3.3 In artificial channels, it is frequently possible to determine the depth downstream at various rates of flow approximately, for example by means of a friction formula if the channel is long enough and of constant slope or by reference to the characteristics of controlling features downstream.

11.3.4 If the flume is to be installed in an existing channel or stream, the following information should then be obtained at the site :

a) The maximum depth recorded with an estimate of the rate of flow at that depth.

b) The approximate depths at two or more intermediate rates of flow.

c) The dead water level in the stream, i.e. the level under zero flow conditions.

11.4 Evaluation of discharge

11.4.1 The basic discharge equation for flumes with trapezoidal throated flumes is given in 9.2.3 and may be expressed as :

$$Q = \left(\frac{2}{3}\right)^{3/2} \sqrt{g}\, C_v\, C_s\, C_D\, b\, h^{3/2} \qquad \ldots (29)$$

The modular discharge coefficient, C_D, is given by an expression analogous to that for a rectangular flume as given in equation (24).

$$C_D = \left(1 - 2\eta \frac{\delta_*}{L} \times \frac{L}{b}\right)\left(1 - \frac{\delta_*}{L} \times \frac{L}{h}\right)^{3/2} \qquad \ldots (30)$$

where

η is a function of m;

m is the slope of flume sides (m horizontal to 1 vertical).

For installations with a good surface finish δ_*/L can be taken as 0,003 and equation (30) reduces to

$$C_D = \left(1 - 0{,}006\, \eta \frac{L}{b}\right)\left(1 - \frac{0{,}003\, L}{h}\right)^{3/2} \qquad \ldots (31)$$

The value of η is obtained from figure 7 and the value of the modular discharge coefficient is then obtained by substituting known values of η, L, b and h in equation (31).

11.4.2 Annex D describes a method of determining C_D from equation (30) taking into account the variability of δ_*/L.

11.4.3 The value of C_v can be computed from equations (16) and (18) making the assumptions that $b_e = b$ and $h_e = h$. Alternatively, figure 6 may be used in association with the calculated value of A using equation (18).

11.4.4 The value of C_s to be inserted in equation (29) is a function of mH_{ce}/b_e and this is given in figure 8. If it were accurate to assume that $H_{ce} = h$, the gauged head, the use of the basic equation to evaluate discharge would be direct, though perhaps tedious. Initially it can be assumed that $H_{ce} = h$. However, to perform an accurate calibration, or accurately to deduce the discharge for a spot measurement of head, successive approximation is necessary, using the equation :

$$\frac{mH_{ce}}{b_e} = \frac{mh_e}{b_e} \times C_v^{2/3} \qquad \ldots (32)$$

For practical purposes it is sufficiently accurate to make the assumption that $h_e \approx h$ and $b_e \approx b$ giving a more readily usable expression :

$$\frac{mH_{ce}}{b_e} = \frac{mh}{b} \times C_v^{2/3} \qquad \ldots (33)$$

11.4.5 The computation of discharge to the first approximation for a given head acting on a trapezoidal flume of known geometry is thus made as follows :

a) List the values of m, m_a, b, B, p, L and g.

b) Compute the area of the approach channel cross-section using equation (17) or equation (18) or equation (19) depending on the shape of the approach channel.

c) Calculate $\eta = \sqrt{(1 + m^2)} - m$, or obtain from figure 7.

d) Calculate C_D from equation (31) using known values of η, L, b and h.

e) As a first approximation, assume $mH_{ce}/b_e \approx mh/b$ and obtain C_s from figure 8 for the given value of h.

f) Obtain the initial value of C_v from figure 6 assuming that $h_e \approx h$ and $b_e \approx b$ and entering the diagram at $C_s bh/A$.

g) Calculate the first approximation value of Q using equation (29) with the above values of C_D, C_s and C_v.

11.4.6 Following the first approximation in 11.4.5 the values of C_s, C_v and Q need refining. C_D holds its final value. The next approximation proceeds as follows :

a) mH_{ce}/b_e is obtained from equation (33).

b) Figure 8 then provides the new value of C_s.

c) $C_s b_e h_e/A$ can now be worked out (assuming $b_e \approx b$ and $h_e \approx h$), and a new value of C_v obtained from figure 6.

d) The value of C_D, together with the revised values of C_v and C_s shall then be inserted in equation (29) to obtain a more accurate figure for Q.

11.4.7 The procedure carried out in 11.4.6 shall be repeated until sufficient precision has been obtained. An example of the method of computation of discharge is given in annex E.

11.5 Computation of stage-discharge relationship

11.5.1 Select a range of values of d_c, the critical depth in the throat, (a roughly logarithmic series is more convenient than an arithmetic one) and for each value proceed as follows :

a) $w_c = b + 2md_c$ $\qquad \ldots (34)$

b) $A_c = (b + md_c)\, d_c$ $\qquad \ldots (35)$

c) Calculate Q using equation (13)

d) Calculate H_e using equation (14)

11.5.2 The next stage is to calculate the head correction, $H_* = H - H_e$. For installations with a good finish δ_*/L can be taken as 0,003 and H_* can be derived but substituting this value in the expression :

$$H_* = \frac{P_c}{w_c} \times \frac{\delta_*}{L} \times L \qquad \ldots (36)$$

where

$$P_c = b + 2d_c\,(1 + m^2)^{1/2} \qquad \ldots (37)$$

If the surface finish is not smooth the value of δ_*/L can be obtained as described in annex D. Substitution of the calculated value of δ_*/L in equation (36) gives the value of H_* taking into account the variability of δ_*/L.

11.5.3 For each value of d_c, calculate the total head, $H = H_e + H_*$. The values of Q and H derived in 11.5.1 and 11.5.2 provide the total head discharge relationship for the flume.

11.5.4 To convert from the total head, H, to gauged head, h, the expression

$$h = H - \frac{\bar{v}_a^2}{2g} \qquad \ldots (38)$$

shall be used, where $\bar{v}_a$ is the mean velocity in the approach channel at the gauging section. In applying equation (38), the geometry of the approach channel shall be used to compute its cross-sectional area A_a. Assuming this to be of trapezoidal section, the appropriate equation is

$$A_a = (h + p)\,[B + m_a\,(h + p)] \qquad \ldots (39)$$

where

p is the height of the hump at the throat;

B is the bed width of the approach channel;

m_a is its side slope (m_a horizontal to 1 vertical).

11.5.5 Because h occurs implicitly in the right hand side of equation (38), a method of successive approximation is needed to determine h.

First approximation :

Set $h = H$ and hence calculate A_{a1} from equation (39). Insert $\bar{v}_{a1}$ in equation (38), where $\bar{v}_{a1} = Q/A_{a1}$, and thus obtain h_1.

Second approximation :

Obtain A_{a2} from equation (39) inserting $h = h_1$. Hence $\bar{v}_{a2} = Q/A_{a2}$ and $h_2 = H - \bar{v}_{a2}^2/2g$.

Third approximation, etc.

Repeat procedure until $h_n - h_{n-1}$ is too small to have a significant effect on the accuracy.

11.5.6 Having thus worked out pairs of values of Q and h for a series of values of d_c, the calibration curve for the flume may be plotted to large logarithmic scales. Discharge values for intermediate values of h may be read off as necessary. Note that the calibration curve is not a straight line on a log-log plot.

11.5.7 An example of the calculation of the stage-discharge relationship for a trapezoidal flume (with and without boundary layer corrections) is given in annex E.

11.6 Graphical approach to design

11.6.1 There is considerable flexibility in the design of a trapezoidal throated flume, and this permits the designer to select values of m and b which will provide a close match to a predetermined relationship of head-to-discharge at two flows. For design purposes an approximate formula which effectively assumes $C_D = 1{,}0$ is adequate.

11.6.2 A convenient graphical method has been derived, using equation (29) in the form

$$\frac{Q}{\frac{2}{3}\sqrt{\left(\frac{2}{3}g\right)}\; bH^{3/2}} = f\left(\frac{mH}{b}\right) \qquad \ldots (40)$$

on the assumption that $H = H_c$ for design purposes.

11.6.3 Required values of Q and H are estimated from a knowledge or estimate of the existing stage-discharge relationship at the site, paying due regard to the head loss needed for free flow, practical limitations on the height of the throat above the stream bed (it shall not be below "no flow" level), and other limitations given. The two values of

$$\frac{Q}{\frac{2}{3}\sqrt{\left(\frac{2}{3}g\right)}H^{3/2}} \qquad \ldots (41)$$

corresponding to these boundary conditions are worked out and plotted on transparent material against H as abscissa on the same logarithmic scales as in figure 9.

11.6.4 Vertical and horizontal guidelines are added to the overlay and the $x = 1$ and $y = 1$ co-ordinates are marked. Move the overlay, keeping the axes parallel with figure 9, until the two plotted points lie on the curve. The intercept of $y = 1$ on the overlay with the y-axis of figure 9 gives $1/b$ and the intercept of $x = 1$ on the overlay with the x-axis of figure 9 gives m/b and hence m.

11.6.5 An example is shown by dotted lines for which $Q\Big/\left[\frac{2}{3}\sqrt{\left(\frac{2}{3}g\right)}\; H^{3/2}\right]$ and H values are 3,07, 2,82m; 1,34, 0,21m; corresponding to discharges of 24,8 m^3/s and 0,22 m^3/s respectively. These requirements are met by a flume in which $b = 1{,}22m$ and $m = 0{,}90$.

11.7 Limits of application

11.7.1 The practical lower limit of h is related to the magnitude of the influence of fluid properties and boundary roughness. The recommended lower limit is 0,05 m or 0,05L, whichever is the greater.

11.7.2 h/L should not exceed 0,50. This limitation on h/L arises from the necessity to ensure parallel flow conditions at the critical section in the throat. h_{max}/L may be allowed to rise to 0,67 with an additional uncertainty in coefficient of 2 %.

11.7.3 The ratio of areas of the approach channel and the throat should preferably be such that the Froude number, Fr, in the approach channel does not exceed 0,5 at any discharge. This shall be checked at each end of the range, and at intermediate flows, using the equation

$$Fr_a = \bar{v}_a/\sqrt{(g\,A_a/w_a)} \qquad \ldots (42)$$

11.7.4 It may be necessary in some situations (for example where coarse sediment is being carried which would deposit in the approach channel) to allow Fr_a to rise to 0,6 but, because of surface irregularities at high Froude numbers, the measurement of head and performance of the flume are less certain, and an additional tolerance of 2 % should be allowed when $0{,}6 > Fr_a > 0{,}5$.

11.7.5 Other limitations arise from inadequate experimental confirmation for extreme sizes or geometries :

a) b shall be not less than 0,1 m;

b) h shall not be more than 2 m.

c) At all elevations, the width between the throat walls shall be less than the width between the approach channel walls at the same elevation, i.e. there shall be a contraction wherever the water surface lies.

d) The sloping walls of the throat shall continue upwards without change of slope far enough to contain the maximum discharge to be measured.