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Hydrometry — Measurement of free surface flow in closed conduits

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British Standards

National foreword

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Hydrometry — Measurement of free surface flow in closed conduits

Hydrométrie — Mesurage du débit des écoulements à surface dénoyée dans les conduites fermées

Reference number
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Foreword

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

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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.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard (“state of the art”, for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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

ISO/TR 9824 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 1, *Velocity area methods*.

This first edition of ISO/TR 9824 cancels and replaces ISO/TR 9824-1:1990 and ISO/TR 9824-2:1990, of which it constitutes a technical revision.

Hydrometry — Measurement of free surface flow in closed conduits

1 Scope

This Technical Report provides a synopsis of the methods of flow gauging that can be deployed in closed conduits flowing part full, i.e. with a free open water surface. It provides a brief description of each method with particular reference to other International Standards where appropriate, the attributes and limitations of each technique, possible levels of uncertainty in the flow determinations and specific equipment requirements. The uncertainties quoted herein are expanded uncertainties with a coverage factor of 2 and an approximate confidence level of 95 %.

2 Normative references

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

ISO 772, *Hydrometric determinations — Vocabulary and symbols*

3 Terms and definitions

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

3.1
free surface flow in closed conduits
flow within closed conduits, under the influence of gravity only, and normally having a free surface

4 Characteristics of a closed conduit system

4.1 Physical structure

Closed conduits can be located below ground (e.g. sewer) or above ground (e.g. culvert). Systems constructed underground usually incorporate a means of access through a suitable sized shaft (manhole) sealed at the surface with a secure, but removable, cover. Access shafts may be provided at frequent intervals along the length of the conduit. It is normal to locate shafts at points of structural change in the system, such as bends, or junctions, or where for some reason, inspection or entry to the system may be required. Access will be subject to strict health and safety conditions and operatives may require special training. Also, access may not be allowed during or following a period of rainfall.

4.2 Construction

4.2.1 Material

Conduits can be made from a variety of materials such as dry stone blocks, vitreous clayware, concrete, cast iron, steel, galvanized iron or steel, asbestos and glass reinforced plastic. In addition, the conduit may have been formed out of the natural bedrock.

The roughness of the surface of the conduit may range from smooth to extremely rough. The roughness may be influenced by organic growths, deposits of sediment, rust, cracks, holes and other imperfections.

4.2.2 Cross-sectional shape

Closed conduits are most commonly circular or rectangular in shape. They may also be ovoid, horseshoe, barrel or triangular. For the purposes of this Technical Report, they are considered to range in diameter from 150 mm upwards.

4.3 Flow conditions

Flow in closed conduits can vary from clear water, free from contaminants (e.g. spring flows), to liquids containing both floating and suspended material (e.g. foul sewer), and in some cases effluents of a corrosive nature. The fluid itself may be an admixture of several substances each with its own characteristic properties. Discharges may vary over a wide range from reverse flow, through zero to many cubic metres per second. For some applications, measurement equipment should be capable of withstanding inundation and measuring surcharge flow. The flow, especially that generated from impervious catchments, may exhibit rapid changes in discharge over short durations and may range from subcritical to supercritical.

4.4 Environment

4.4.1 Within the conduit

The atmosphere within a conduit system may be assumed to be in equilibrium with the liquid in the conduit. If the atmosphere is of a toxic and/or corrosive nature, precautions should be taken to protect the equipment from its effects or choose a method for which this is not a problem.

It is possible that under certain circumstances, the atmosphere may be of a potentially highly explosive nature. Therefore, the equipment to be installed within the confines of the conduit system should be intrinsically safe. For example, all electrical circuits should be constructed so that they cannot cause ignition of the atmosphere.

The extremes of the atmospheric environment within which the equipment is expected to operate need to be ascertained in terms of temperature, humidity, pressure and gases.

4.4.2 External environment

Where elements of the equipment are situated outside the conduit system, the external environmental conditions should be ascertained. Examples of these external conditions are

a) atmospheric temperature and relative humidity ranges,

b) likelihood of electrical interference, and

c) likelihood of mechanical shock.

5 Selection of method

5.1 General

In selecting the most appropriate method, the factors in 5.2 should be taken into account.

5.2 Factors

5.2.1 Frequency and duration of measurement

The response of the conduit system to inputs of storm run-off may require measurements to be taken at frequent intervals to allow the hydrograph to be defined. The recording intervals may need to be one minute or less. The duration of flow measurement at a site should be consistent with the intended use of the data.

5.2.2 Physical conditions

The physical conditions that may affect the choice of method are

a) ease of access to the site,

b) dimensions of the conduit,

c) upstream and downstream conduit integrity,

d) junctions, bends, connections, bifurcations, inlets and outlets,

e) bed load, silt load and suspended solids,

f) range of depth and discharge,

g) range of velocity,

h) flow directions,

i) atmosphere within the conduit, e.g. temperature, humidity and quality,

j) the nature and concentration of dissolved, floating and suspended solids. The material/pollutant may be classified into four groups:

    1) pollutants and sediments in solution;

    2) finely suspended sediments with median diameter = 0,062 mm;

    3) coarse sediments where median diameter = 3,5 mm;

    4) gross solids where particulate matter is greater than 6 mm in any two dimensions.

5.2.3 Site surveys

It is desirable that a preliminary survey is made to decide on the suitability of the site taking due account of the various physical conditions as listed in 5.2.2. In addition, it may be necessary to abide by specific national or local health and safety regulations that could be in force for persons working in closed conduits or confined spaces.

6 Methods of measurement

6.1 Volumetric methods

6.1.1 Description

In the volumetric method, the change in level of fluid in a reservoir is measured over time to deduce flow-rate, given a known relationship between fluid depth and volume. Account needs to be taken of any simultaneous inflows and outflows that are occurring. For example, for a wet well system that is emptied by a pump turned on and off by high and low level switches, the inflow may be calculated from the time to fill, i.e. when the pumps are off. The discharge may also be calculated from the time to empty when the pumps are on, assuming that the inflow is constant.

This method may be applied where fluid depth is monitored by fixed point level switches or a continuous level sensor.

Using this method, flow-rate is averaged over the time period to fill or empty the tank, hence short-term peaks or troughs in the instantaneous flow-rate may not be captured. The use of continuous level measurement equipment to take intermediate readings may enable any variations in the flow-rate to be identified.

6.1.2 Attributes and limitations

Fluid level can be measured by non-contact means minimizing maintenance requirements.

This method requires a flow computer but otherwise no additional sensors need be installed, as those already in place to control the pump switching are used.

The method can only be used where there is an appropriate tank, wet well or reservoir.

The volume/depth relationship can be difficult to determine for irregularly shaped reservoirs or those with intrusions and internal structures.

This method is usually not practical in an underground system.

Sediment and sludge building up in the reservoir can change the volume/depth relationship.

6.1.3 Equipment

The following will be needed to apply this method:

a) a suitable reservoir;

b) a means of determining fluid level at two or more points in the reservoir;

c) a suitably programmed flow computer.

6.1.4 Application

This method may either be used for short-term flow surveys, calibration and verification of permanently installed equipment or as a permanent means of measurement.

6.1.5 Uncertainties

The performance of this method is dependent on the certainty with which the volume/depth relationship of the reservoir is known, the resolution and accuracy of the equipment used to measure the fluid depth in the tank and the presence and character of the inflows and outflows. The resolution of the level sensor(s) should be considered against the changes in depth which may be encountered using a reservoir with large surface area, i.e. the volume change in a reservoir with a large cross-sectional area will change greater for a given change in fluid depth than one with a smaller cross-sectional area.

Uncertainties (with a coverage factor of 2 and an approximate confidence level of 95 %) of less than 2 % are achievable for a clean reservoir having a precisely defined volume/depth relationship and using a high resolution depth sensor with an uncertainty within 0,5 %. Generally with a good installation, the uncertainty will be of the order of 5 %.

6.2 Tracer and dilution method

6.2.1 Basic principles

The basis of the tracer and dilution method is to inject a substance into the flow that can be easily distinguished from the bulk liquid and thereafter detect that substance at a point downstream. There are two distinct ways in which the method may be applied:

a) transit time that measures the time taken for a sudden injection of tracer to travel from one point to another;

b) dilution gauging which compares the concentration of the tracer injected into the bulk fluid with the concentration detected downstream of the injection point. This can be further subdivided into constant rate injection or tracer integration methods.

The choice of tracer depends upon the nature of the fluid and the installation. The tracer should not appear in significant quantities in the fluid nor be absorbed by, or react with the fluid or the walls of the conduit. The latter may be a consideration if the walls are subject to biological or chemical fouling.

The three principal types of tracer which are used are

1) radioactive, e.g. Tritium, Na(24) (as sodium carbonate solution), Br(82) (as potassium bromide solution),

2) fluorescent, e.g. Pyranine,

3) chemical, e.g. sodium chloride, lithium chloride, sodium iodide.

The use of radioactive tracers in discharges to sewers or the environment is nowadays generally unacceptable. For water applications, lithium chloride and sodium chloride are the most widely used tracers.

The application of dilution gauging to free surface flows is described further in ISO 9555 (parts1 through 4).

6.2.2 Attributes and limitations

The method has been successfully used across a wide range of applications and is covered by established International Standards.

There is minimal disruption to the flow.

There is a need to ensure good mixing between the injection and sampling points whilst keeping this distance as short as possible. ISO 2975 looks specifically at the requirements to ensure good mixing. To help mixing, flow should be fully turbulent, i.e. with a Reynolds number greater than 5 000.

With some tracers, e.g. lithium chloride, results are not available on site as samples require laboratory analysis to determine the tracer concentration. If sodium chloride is used as the tracer, detection may be done using a conductivity sensor to provide an immediate result.

Two access points are required, one for injection and one for sampling.

Flow needs to be kept stable for the duration of the test that may take many minutes.

6.2.3 Equipment

The equipment required for the application of this method comprises: reservoir of tracer solution, timing mechanism, tracer injection apparatus and means for extracting samples or detecting tracer downstream of injection point. For some chemical tracers, access to a laboratory for determination of tracer concentration in the downstream samples will be needed.

6.2.4 Application

These methods are generally used for short-term tests such as flow surveys or for the calibration and verification of permanently installed equipment.

6.2.5 Uncertainties

An uncertainty (with a coverage factor of 2 and an approximate confidence level of 95 %) of 5 % may be expected.

6.3 Flow measurement structures

6.3.1 Basic principles

A flow measurement structure is generally designed to act as a control in the channel in order to provide a unique, stable relationship between head (stage) and discharge. The relationship can usually either be derived empirically or from physical principles. Most flow measurement structures require critical flow to occur at the control section, i.e. the upstream head or water level is independent of downstream conditions. This condition is normally referred to as modular flow. If the upstream water level (head) is affected by downstream conditions, the flow is said to be non-modular. Some structures can still be utilized when the flow is non-modular, but an additional downstream head measurement is required in order to determine a reduction factor that is applied to the modular head-discharge relationship. However, the uncertainty of the flow determination under non-modular conditions will be larger. Therefore, the use of flow measurement structures under non-modular flows should be avoided whenever possible.

For most of the commonly used flow measurement structures, there are International Standards that outline the design requirements and their physical limitations, e.g. minimum head requirements. Reference is made to the relevant International Standards, where appropriate, in 6.3.4.

The performance of a flow measurement structure is dependent on the following factors:

a) the hydraulic and other site conditions over the target discharge range;

b) the quality and accuracy of construction and installation;

c) the accuracy and reliability of the upstream head, and where appropriate downstream head, measurements.

Flow measurement structures cause an obstruction in the watercourse to create sufficient head difference in order to determine flow. When designing or installing flow measurement structures, it is therefore important to establish the impact of the structure on upstream water levels in the channel, i.e. how much afflux or backwater is being created under different flow conditions. It is particularly important when installing flow measurement structures in closed conduits to ensure that the liquid carrying capacity of the conduit is not significantly reduced resulting in the potential to do damage or harm.

Guidelines on the selection of structures are contained in ISO 8368.

6.3.2 The use of flow measurement structures in closed conduits

The use and selection of flow measurement structures in closed conduits will depend on the hydraulic and other physical conditions that prevail. In some closed conduit situations, conventional open channel flow measurement structures for which there are appropriate International Standards may be used. Conversely in some closed conduits where pressure conditions as well as free surface flow conditions occur, or where the hydraulic conditions are unsuitable, it will not be possible to measure flows using conventional structures. For this reason, special types of structures have been designed to operate under such conditions. For the purposes of this Technical Report, flow measurement structures have therefore been categorized under the following headings:

a) special structures appropriate for use in closed conduits or structures for which there is currently no International Standard;

b) conventional structures for which there is an International Standard.

6.3.3 Special structures not covered by any specific International Standard

These are summarized in Table 1.

Table 1 — Special structures for use in closed conduits not covered by a specific International Standard

Type	Figure number	Comments, attributes and limitations	Applications
Vertical slot weir	1	Allows solid materials to pass the installation. Rating curve may be affected by the conduit slope and roughness, particularly for wide slots at low flows.	Larger conduits carrying solid materials, where there is free surface flow
Trapezoidal weir	2	Allows passage of solids and does not obstruct flow. Rating curve is affected by the conduit slope and roughness, but can measure lower depths and smaller flows than vertical slot weir.	Larger conduits carrying solids and where there is free surface flow
US Geological Survey (USGS) meter	3	Device that acts as a flume under free surface flow conditions and a nozzle when surcharged. Under the free surface flow conditions, the greater the constriction, the better the accuracy.	Closed conduits where both free surface and surcharge conditions will occur
University of Illinois meter	4	Similar to USGS meter. The transition from free surface to pressure flow is not as smooth however, owing to the shape of the constriction in the conduit soffit.	Closed conduits where both free surface and surcharge conditions will occur
Palmer-Bowlus Flume	5	A critical depth flume that has been tested in sloping conduits and exhibits a successful head-discharge calibration for both subcritical and supercritical free surface flow. Modifications to the design are recommended to improve the head-discharge relationship in the transition zone from free surface to pressure flow.	Larger conduits

Dimensions in metres

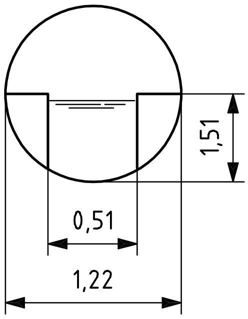
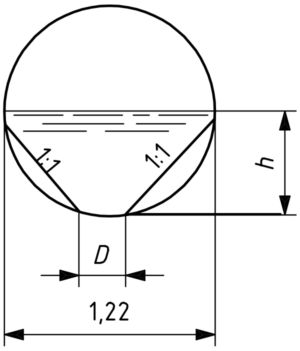


Figure 1 — Vertical slot weir

Dimensions in metres

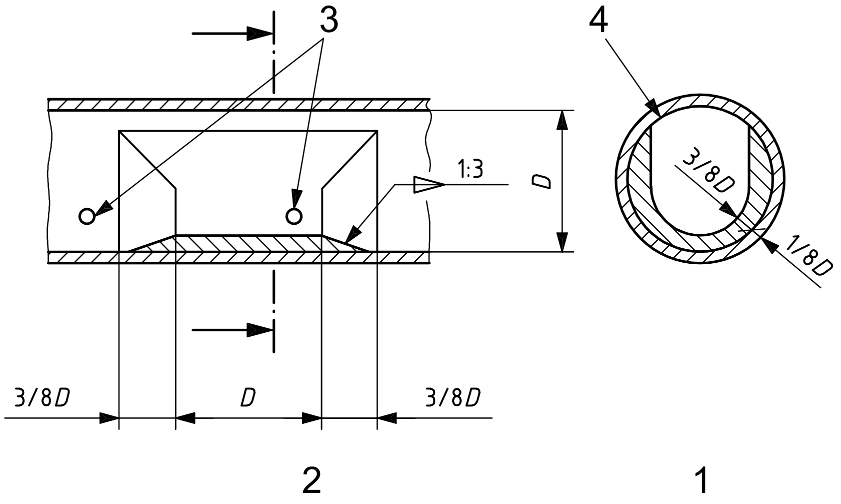


Key

D internal diameter of the conduit

h head

Figure 2 — Trapezoidal weir

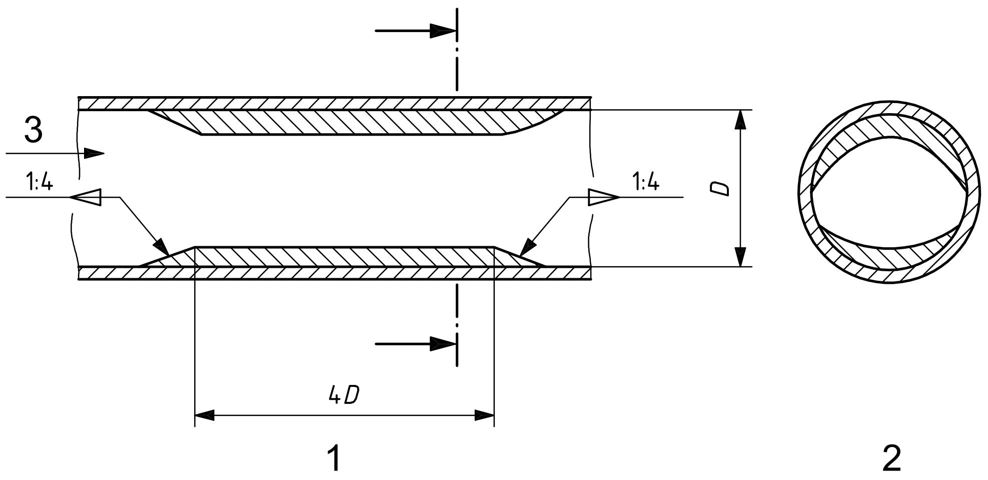


Key

1 throat cross section
2 side view
3 piezometer taps
4 $\frac{\text{throat area}}{\text{pipe area}} = 0{,}709$

D internal diameter of the conduit

Figure 3 — US Geological Survey (USGS) meter

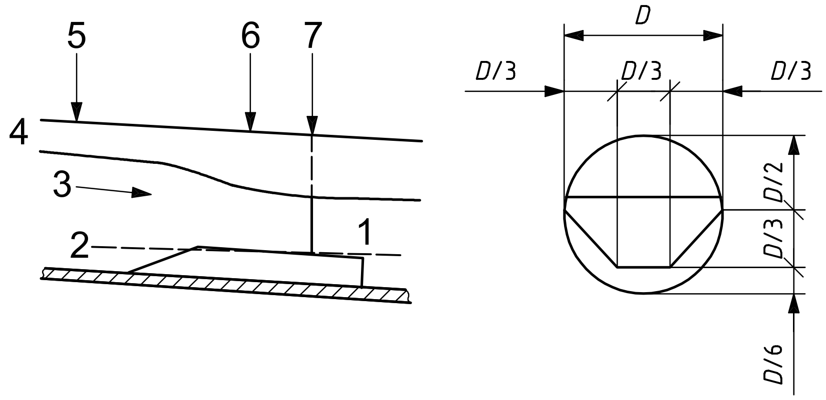


Key

1 throat cross section
2 critical section
3 flow

D internal diameter of the conduit

Figure 4 — University of Illinois meter



Key

1 throat zero datum

2 approach zero datum

3 flow

4 water surface

5 approach section

6 critical section

7 throat section

D internal diameter of the conduit

$D/2$ half the diameter of the conduit

$D/3$ one third of the diameter of the conduit

$D/6$ one sixth of the diameter of the conduit

Figure 5 — Palmer-Bowlus flume

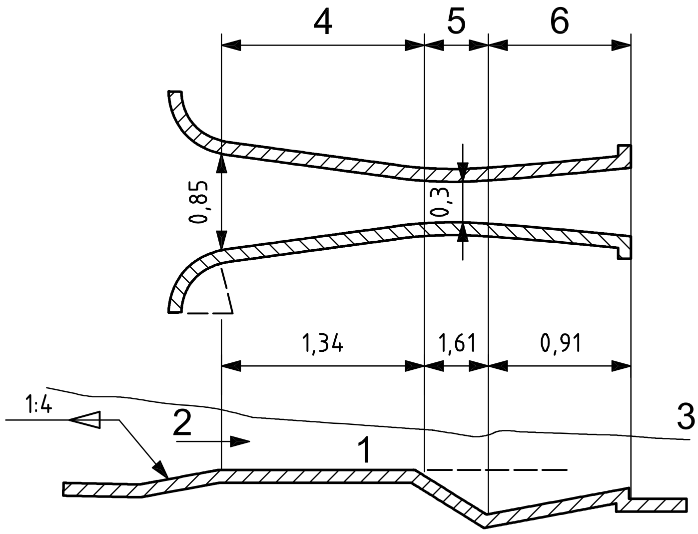
6.3.4 Conventional structures

These are summarized in Table 2.

Table 2 — Conventional structures with International Standards

Type/ ISO International Standard number	Figure number	Comments, attributes and limitations	Applications
Parshall flume/ ISO 9826	6	Critical depth flume originally developed for use in irrigation canals.	Free surface flows in larger conduits
Thin plate weirs/ ISO 1438-1	7 and 8	Rectangular thin plate weirs and V–notches are relatively easy to install but manufacture of crest requires care. Accurate. V-notches can be particularly suitable where ratio of high to low flows is large and low flow accuracy important. Susceptible to poor approach conditions and high sediment loads.	Free surface flows in sediment free water, e.g. spring flows
Triangular profile weirs/ ISO 4360	9	Good accuracy, discharge range and modular limit. Relatively robust and have the ability to pass heavy silt. Can be used under non-modular conditions if crest tapping and/or downstream head measurements are made.	Free surface flows in larger conduits with large amounts of suspended solids
Triangular profile flat-v weir/ ISO 4377	10	Have similar attributes to horizontal crested triangular profile weirs but have greater sensitivity.	Free surface flows in larger conduits with large amounts of suspended solids
Flumes: Rectangular and U-shaped/ ISO 4359	11 and 12	Flumes are often recommended where material is being transported along the conduit. Suitable where afflux needs to be kept to minimum. Rectangular flumes in particular can be relatively cheap to install. They are universally used for measuring inflows to waste water treatment works.	Free surface flows Rectangular flumes in rectangular conduits and U-shaped flumes in circular sewers and other conduits

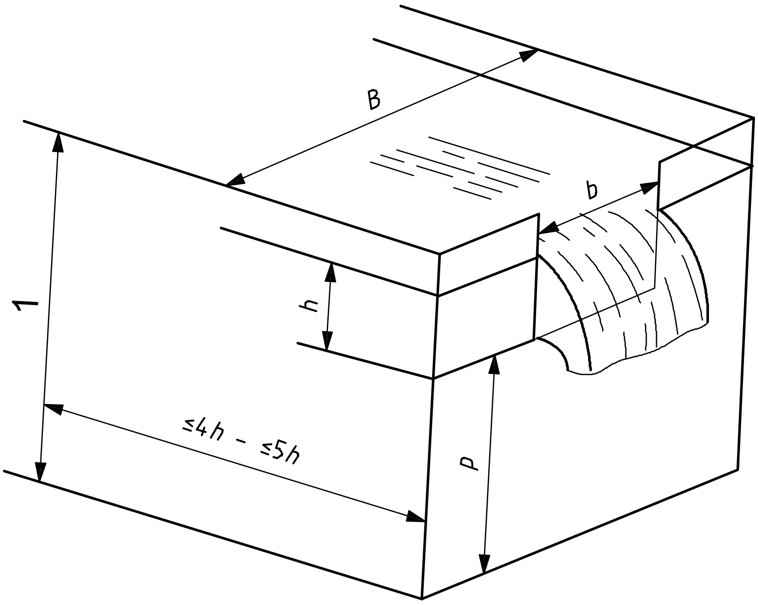
Dimensions in metres



Key

1 level floor
2 flow
3 water surface
4 converging section
5 throat section
6 diverging section

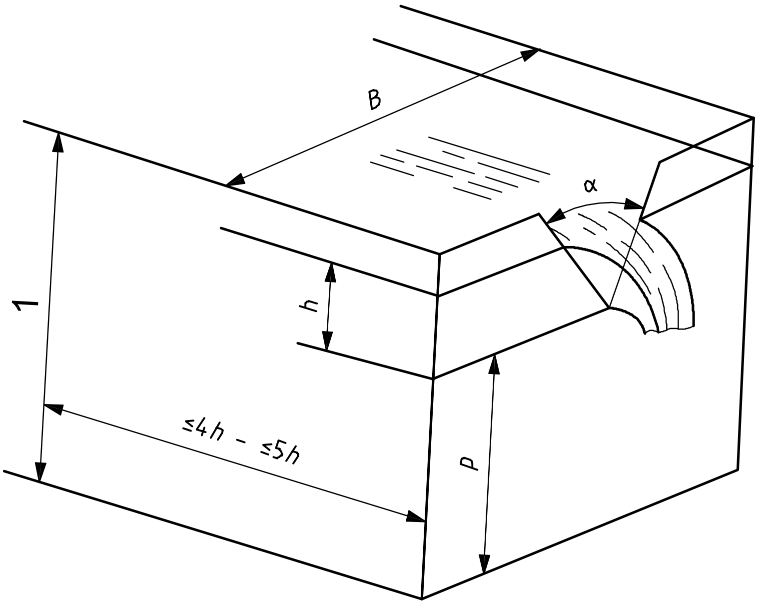
Figure 6 — Parshall flume



Key

1	head measurement section	*h*	head
b	measured width of notch	*p*	height of crest
B	width of approach section		

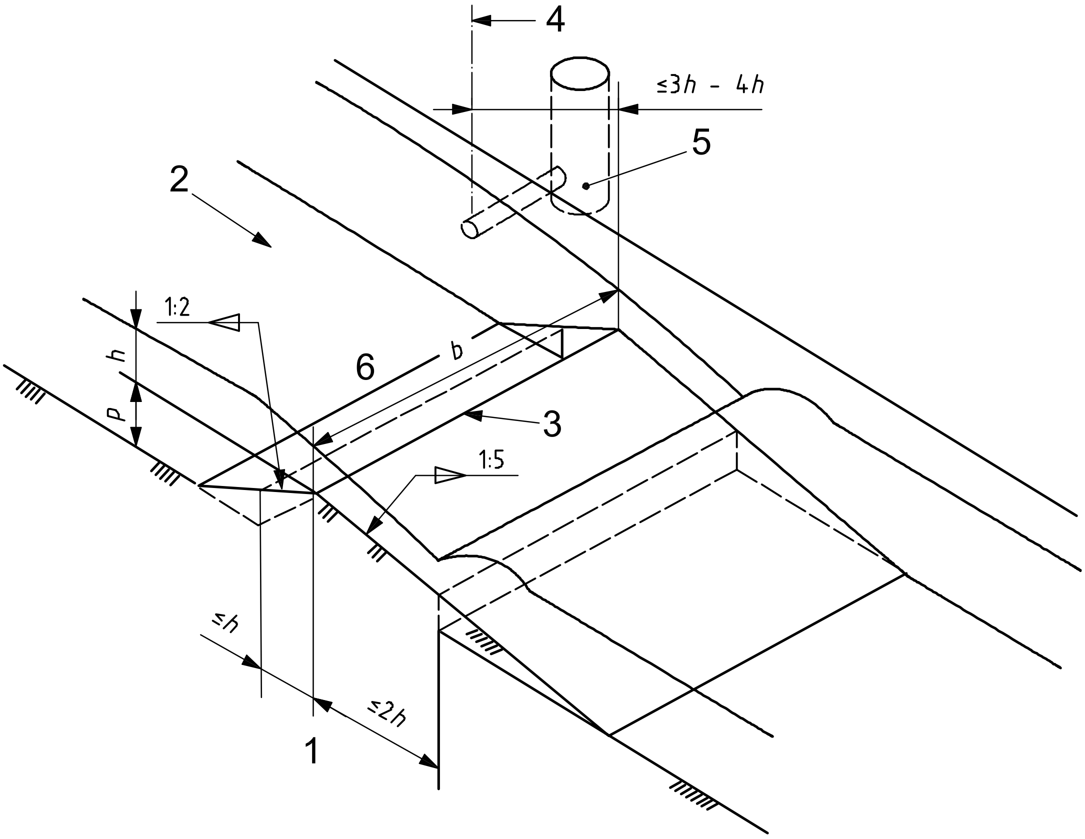
Figure 7 — Rectangular thin plate weir



Key

1	Head measurement section	*h*	head
α	notch angle, i.e. angle included between sides of notch	*p*	height of apex of V-notch above bed
B	width of the approach channel		

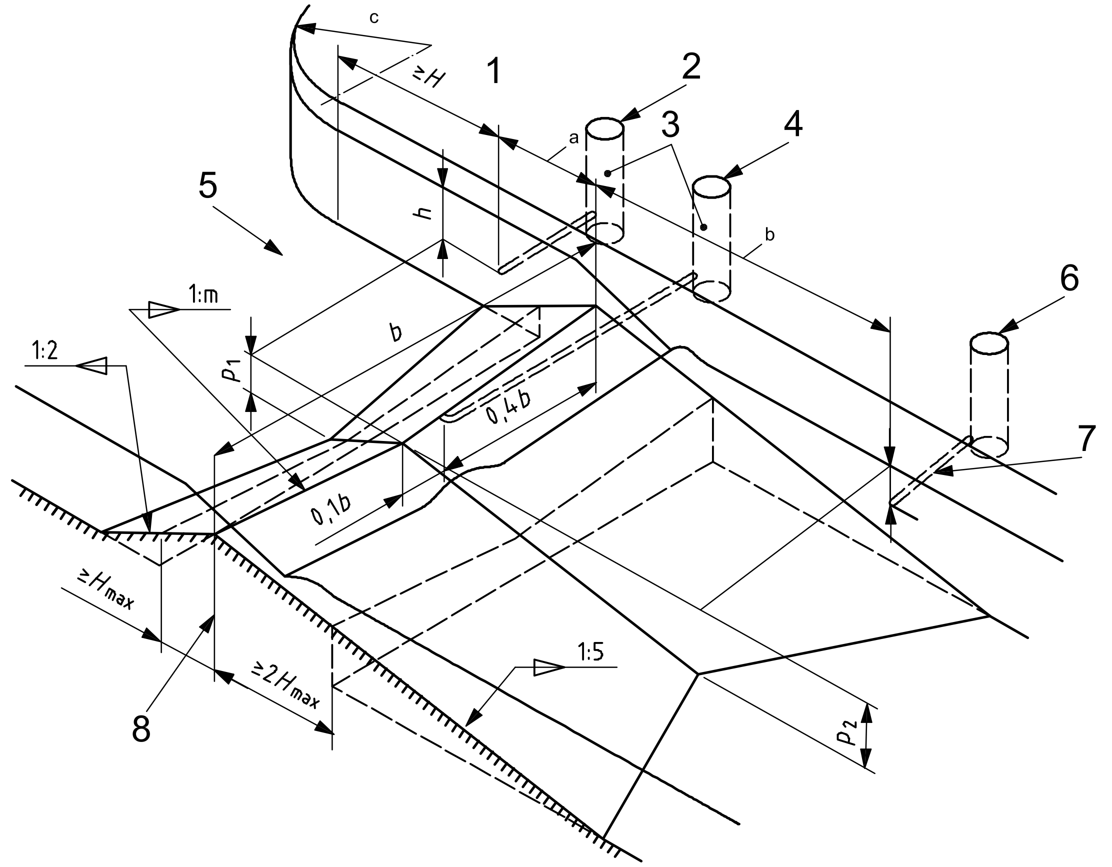
Figure 8 — V-notch thin plate weir



Key

1	permissible truncation
2	flow
3	crest
4	head measuring section
5	stilling well
6	toe
b	width of the weir crest
h	head
p	difference between crest elevation and upstream bed level

Figure 9 — Triangular profile weir



Key

1 head measuring section
2 upstream tapping
3 stilling wells
4 crest tapping
5 flow
6 downstream tapping
7 100 mm above stilling basin level
8 permissible truncation

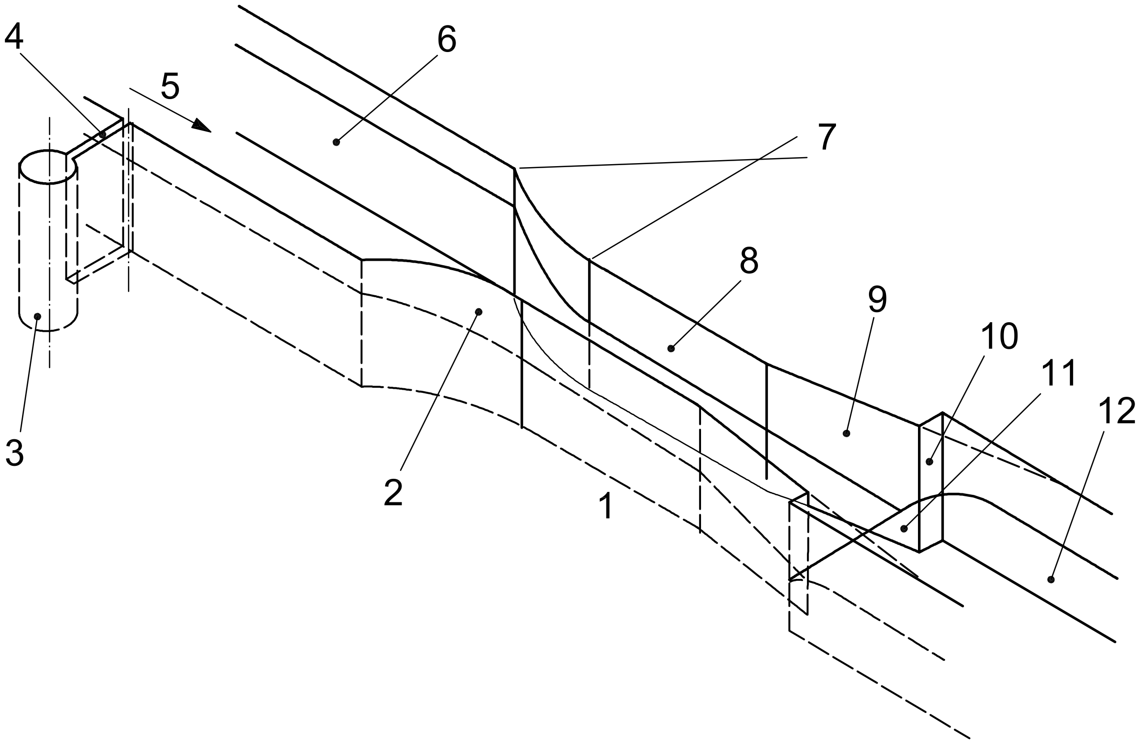
b	width of structure
R	radius of wing walls at upstream end of structures
h	head (static head or stage reading measured relative to minimum crest level)
H	total head (static head plus velocity head)
H'	height of ‘v’ section
H_{max}	maximum total head
p_1	difference between minimum crest level and upstream bed level
p_2	difference between minimum crest level and upstream bed level

[a] $10H_{\Delta}$ but $\leqslant 3H_{max}$

[b] $25H_{\Delta}$ but $\leqslant 3H_{max}$

[c] $R \geqslant 2H_{max}$

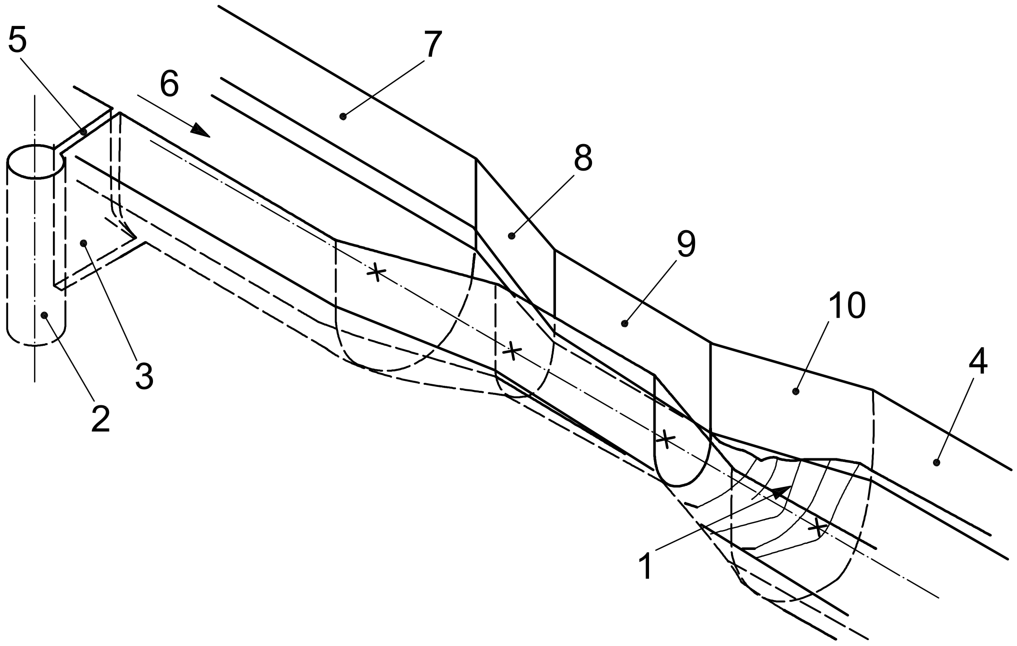
Figure 10 — Triangular profile flat-v weir



Key

1 horizontal invert
2 entrance transition
3 stilling well
4 connecting slot
5 flow
6 approach section
7 entrance transition
8 throat
9 exit transition
10 example shown of truncation
11 standing wave
12 exit section

Figure 11 — Rectangular flume



Key

1 standing wave
2 stilling well
3 connecting slot
4 exit channel
5 flow
6 approach section
7 entrance transition
8 throat
9 exit transition

Figure 12 — U-shaped flume

6.3.5 Equipment

Equipment suitable for the measurement of water levels in open channels is described in ISO 4373, to which reference should be made. The selection of a suitable water level sensor will be dependent on site conditions.

In many closed conduit situations, it is possible that the installation of a stilling well will not be cost-effective or technically feasible. This would rule out the use of a float and counterweight system. However, in many closed conduit situations turbulence and oscillation may be a problem. Therefore, a sensor and logging system with inbuilt electronic stilling/damping may be required.

In water that is heavily silt laden or carrying foul or toxic effluent, an air-ranging ultrasonic water level gauge may be the preferred option. Care must be taken to ensure that the minimum blanking distance can be maintained or that the equipment does not become submerged.

For sites where free surface flow and pressure flow may occur, a pressure transducer may provide the best option.

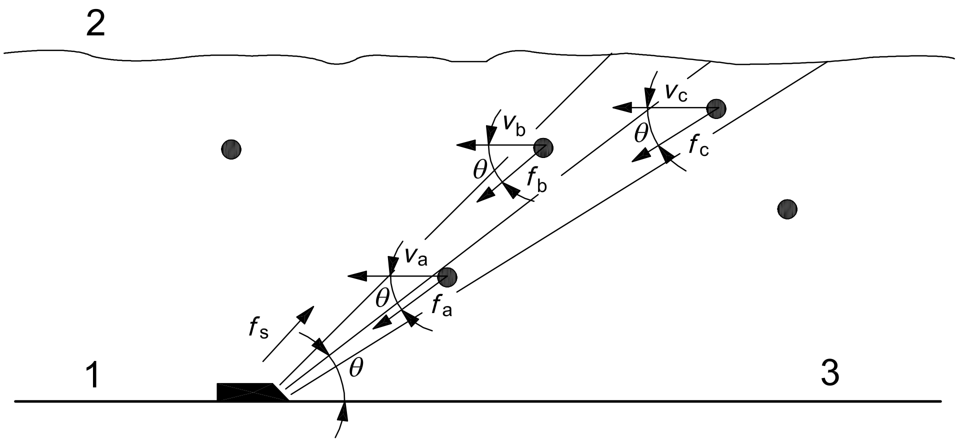
6.3.6 Uncertainties

It should be possible to determine discharges to an uncertainty (with a coverage factor of 2 and an approximate confidence level of 95 %) of within 5 %, using conventional flow measurement structures operating under modular conditions, provided the physical conditions, design, construction and operation are in accordance with the appropriate International Standard.

6.4 Ultrasonic Doppler

6.4.1 Basic principles

The ultrasonic Doppler technique is based on the Doppler Shift concept. Pulses of ultrasound are transmitted at an angle into the water body at the measuring section (see Figure 13). The sound is reflected from particles in the water back to the transmitter, which also acts as a receiver. The difference in frequencies of the transmitted and reflected sound is proportional to the velocity of the particle (reflector). The velocity of the particle is assumed to be equal to the velocity of flow of water at that point. The reflections from a number of particles are analysed by the Doppler meter and an estimate of the mean velocity in the measuring section is made. Depth measurements are made, often by means of a pressure transducer built into the velocity sensor, at the same time as the velocity measurements. If the relationship between depth and area for the measuring section is known, it is possible to estimate the flow by multiplying the velocity by the area.



Key

1	Doppler sensor
2	water surface
3	channel bed
a, b and c	particulates
f_s	frequency of transmitted sound pulse
f_a, f_b and f_c	frequency of sound pulses reflected from particulates a, b and c
v_a, v_b and v_c	velocity of particulates a, b and c
θ	angle between the horizontal and the angle of the sound beam

Figure 13 — An illustration of the principle of Doppler flow monitoring technology

The technique has been widely used for measuring flows in pipes and sewers for a number of years. However, it has not yet been so widely used in open channels, particularly natural streams and rivers. Nevertheless, this type of use is on the increase since the costs of supply and installation, and the environmental impacts of ultrasonic Dopplers are invariably less than flow measurement structures. The technique is particularly suitable for many closed conduit applications.

The amount of spread of the sound beam, and thus the cross-sectional area of flow sampled, is a function of the design of the Doppler velocity meter, the number of reflectors in the water and other physical characteristics. Some ultrasonic Doppler systems only measure the strongest reflected signals, whereas other systems try to sample a larger area by analysing weaker signals. A third type of Doppler system, sometimes referred to as 'range gated' or 'time gated', divides the sampled cross section into a number of cells (sometimes referred to as 'bins') and estimates the mean velocity in each cell.

Most ultrasonic Doppler systems are fixed to the bed of the watercourse, channel or conduit. However, if the sensor is likely to be covered by silt or water borne debris, it may be necessary to raise it by spacing it off the bottom, to displace it off-centre in circular conduits or to side mount it. One type of Doppler system is designed to be side mounted and estimates the mean velocity across the channel at a fixed level. As such, it is similar to a single-path 'transit time' ultrasonic system (see 6.5).

The technique is described more fully, along with guidelines for usage in ISO/TS 15769.

6.4.2 Attributes and limitations

Ultrasonic Dopplers are usually relatively cheap, simple and easy to install and in large conduits tend to be relatively non-obstructive. Manufacturers usually supply fixing bands for different conduit diameters for ease of installation. Ultrasonic Dopplers are bi-directional enabling the measurement of reverse flows.

One of the main limitations of the technique, particularly in larger, irregular channels, is knowing what portion of the cross section is being sampled. This is often not a major problem in closed conduits. Depths in excess of 0,1 m are normally required. Also, it is recommended that ratios of channel depth to width of less than 0,2 should be avoided. In very clean water, e.g. spring flows, there may not be sufficient reflectors in the water for the effective operation of some Doppler systems. Conversely, a very high level of suspended solids provides good local signals but may limit the range of sampling (measurement).

If the conduit is flowing under pressure, the depth sensor will overestimate the depth. This is not a problem provided the pressure does not exceed the manufacturer's recommended maximum pressure, since the depth area table or relationship can be capped at pipe full.

6.4.3 Equipment

The equipment normally consists of velocity and depth sensors, connecting cable and data logger. In some systems, the data logger is built into the sensor head. The choice of Doppler will depend on the user's specific data requirements and the physical characteristics of the site. ISO/TS 15769 includes a sample questionnaire that offers a structured step-by-step approach, helping to focus on key issues that govern the overall suitability and performance of the Doppler flow measurement technique.

6.4.4 Applications

The ultrasonic Doppler technique is applicable to closed conduits greater than 300 mm wide or diameter, with depths of flow greater than 100 mm, but generally not exceeding 3 m width and 2 m depth.

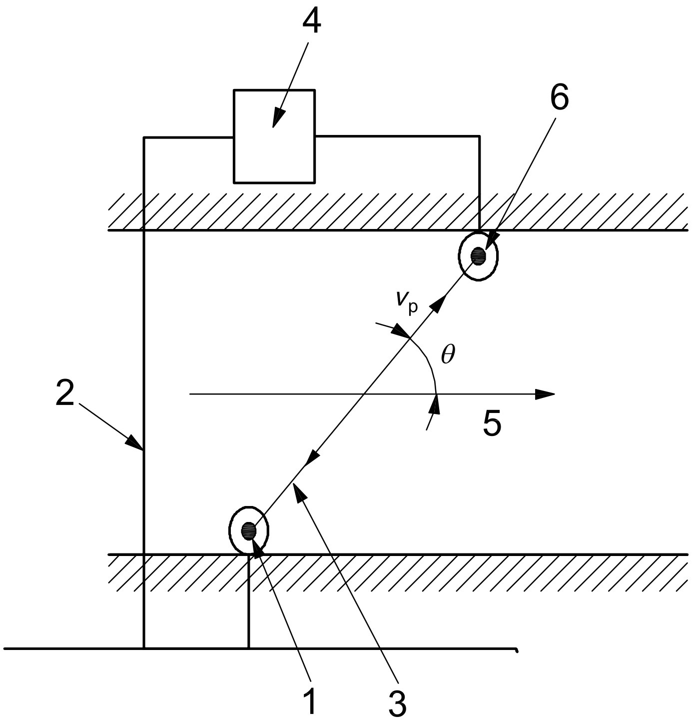
6.4.5 Uncertainties

It should be possible to determine discharges to an uncertainty (with a coverage factor of 2 and an approximate confidence level of 95 %) within 10 % using ultrasonic Doppler systems, provided the physical conditions, design, construction and operation are in accordance with the manufacturer's recommend guidelines and ISO/TS 15769.

6.5 'Transit time' ultrasonic flow meters

6.5.1 Basic principles

'Transit time' ('time of flight') ultrasonic flow measurement is based upon the principle that when sound pulses are transmitted at an angle to the direction of flow (see Figure 14), the speed of the pulse in the downstream direction will be enhanced by the flow of water, whilst, returning in the upstream direction, the speed of the pulse will be impeded by the flow.



Key

1 transducer
2 cable duct
3 flight path
4 instrumentation shelter, kiosk or building
5 flow
6 transducer

v_p the path velocity, i.e. the velocity in the direction of the line of the transducers

Figure 14 — Sketch illustrating the principle of 'transit time' ultrasonic flow measurement

The velocity in the direction of flow at the elevation of the sound transmitting and receiving transducers is related to the different sound pulse travel times as follows:

$$v_y = \frac{L}{2\cos\theta}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \qquad [1]$$

where

v_y is the average velocity in the direction of flow at level, y;

θ is the angle between the direction of flow and the flight path;

t_1 is the time to travel along the flight path with the flow;

t_2 is the time to travel along the flight path against the flow;

L is the length of flight path.

For single-path systems, the estimated velocity is used directly to derive the mean velocity in the measuring section. In multi-path systems, the cross section is normally divided into a number of horizontal segments or slices defined by the positions of each pair of transducers in the vertical. The velocities derived for different paths are then used to derive the flow in their assigned segments by multiplying the mean velocity in the segment by the area of the segment. The flows in each segment are then summed together to provide an estimate of the total flow in the entire cross section. If there is an error of greater than a few degrees in the determination of the angle between the direction of flow and the flight path (θ), large errors can occur in the determination of the velocity. Such errors can occur when skew flow occurs. In order to minimize this type of error, cross-path systems are installed. Cross-path systems are where a second line of transducers is installed diametrically opposite the first. Discharges are usually computed separately for each line of transducers and averaged to compensate for skew flow.

Depth measurements are also required in order to determine the area of flow for the estimation of discharge.

‘Transit time’ ultrasonic open channel flow gauges have been used successfully on small artificial channels 0,5 m wide to larger rivers with widths up to at least 500 m.

The technology is also used for pipe flow measurement. For pipe flow measurement, it is possible to obtain clamp-on units whereby the transducers can be clamped onto the outside of the pipe. As these units require the pipe to be running full, they are not suitable for measuring flows in closed conduits with a free water surface.

The technique is described in detail in ISO 6416.

6.5.2 Attributes and limitations

‘Transit time’ ultrasonic systems are usually relatively easy to install, are non-obtrusive, can be highly accurate (see 6.5.4) and can often be more cost-effective than other feasible alternatives. ‘Transit time’ ultrasonic flow gauges are bi-directional enabling the measurement of reverse flows.

Excessive attenuation of the acoustic signal can occur due to high levels of suspended solids, entrained gases and temperature gradients. Nevertheless, the technology is now used for measuring raw effluent at the inlets to waste water treatment works where the ultrasonic path lengths are short and the attenuation can be tolerated. However, sensor fouling can be a problem when measuring raw sewage, and, at least requires regular maintenance. There is also a minimum depth requirement that is a function of the frequency of the transducers and the length of the flight path. A limitation of the technique when using systems with only one path or a limited number of paths, is the fact that as the water level changes, the system will be sampling a different part of the velocity distribution. In such cases, it is necessary to determine a relationship between measured velocity and the mean cross-sectional velocity. This is described in ISO 6416.

6.5.3 Equipment

The equipment normally consists of pairs of ultrasonic transducers (these can be mounted on fixing racks on the insides of the conduit), a depth sensor, connecting cables, electronic control unit and a data logging system. Another method of fixing in closed conduits is on rings either bolted to the inside or expanded into position and secured by friction.

The choice of depth sensor will be dependent on the site conditions. Low range pressure transmitters and air ranging ultrasonic depth sensors (provided there is enough free air space above the maximum water level) may be appropriate for many applications.

6.5.4 Applications

Closed conduits with widths or diameters greater than 0,5 m and minimum depths of flow generally greater than 0,1 m. If it is proposed to use the technique in closed conduits with high levels of suspended solids, advice should be obtained from the supplier before purchase.

6.5.5 Uncertainties

The uncertainty in the determination of flow is a function of the number of transducer paths that are operational. Generally, the greater the number of paths, the better the overall determination of discharge. For systems with four or more operational paths, the uncertainties (with a coverage factor of 2 and an approximate confidence level of 95 %) should be within 5 %. Even with single-path systems, it should be possible to estimate discharges to within 10 % provided the line velocity can be reliably related to the mean velocity in the cross section of flow over a wide range of flow conditions. The calibration of single-path ‘transit time’ ultrasonic systems is described in ISO 6416.

6.6 Electromagnetic method

6.6.1 Basic principles

6.6.1.1 General

Fluid velocity can be measured using Faraday’s principle. This states that a conductor moving within an electromagnetic field will generate a voltage mutually perpendicular to the direction of movement and the magnetic field. The voltage generated is proportional to the velocity of the fluid, thus in order to obtain volumetric flow, a determination of the cross-sectional area of the flow also needs to be made. This is generally calculated from the measurement of the fluid depth and knowledge of the shape of the conduit. There are three formats of sensor for measurement in conduits with free surface flows. These are discussed in 6.6.1.2 through 6.6.1.4. Also see Figure 15.

6.6.1.2 Local velocity sensor

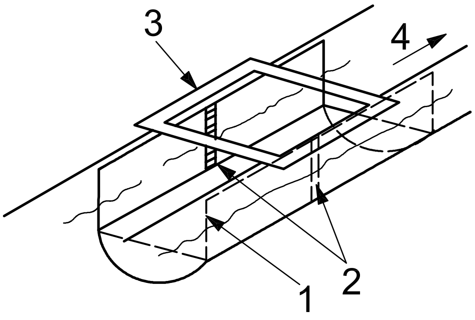
A small sensor assembly is mounted on the invert of the conduit. The sensor houses the coil to generate the magnetic field and the measurement electrodes for detecting the induced voltage. A third electrode may also be included to locally earth the fluid ensuring that the measured voltages are correctly referenced. A pressure sensor may also be incorporated into the assembly to measure the fluid depth. Alternatively, depth may be measured by a separate sensor, with the two units linked to a flow computer. The velocity sensor may be mounted on an expanding stainless steel band for insertion into sewers and other closed conduits.

6.6.1.3 Full width sensor

A coil is buried below the channel bed or mounted above the conduit. In some installations, a single coil will be used to cover the full width of the conduit. In others, one or more prefabricated units each containing a coil assembly may be placed at intervals across the conduit. These will be linked to a single flow computer that will combine their signals to derive a single bulk flow measurement.

Electrodes set into the channel walls measure the resulting voltage generated. An insulating section, or membrane, must be built around the electrodes which adds to the cost and complexity of the installation. This insulating section is necessary to avoid attenuation of the induced signal by electrical conductive leakage through the conduit walls and surrounding ground.

This method is described further in ISO 9213.



Key

1 membrane
2 electrodes
3 field coil
4 flow

Figure 15 — Electromagnetic method

6.6.1.4 Spool piece sensors

A number of manufacturers have incorporated the magnetic coils and measurement electrodes into an insulated flow tube to form a spool piece sensor for installation in place of a length of conduit. These devices differ from conventional electromagnetic closed pipe flow meters in that they have been specifically designed for pipes running partially filled. The electromagnetic method is used to determine fluid velocity and a second method used to measure fluid depth. These meters are capable of measuring under surcharged conditions and use a number of means to determine when that occurs. This then triggers the meter to behave as a conventional electromagnetic closed pipe flow meter. Means used to measure depth include the following:

a) a number of electrode pairs spaced around the lower half of the sensor, depth being deduced from the coverage of each pair;

b) capacitative level sensors embedded in the sensor walls;

c) top-down ultrasonic level sensors;

d) hydrostatic level sensors on the pipe invert.

6.6.2 Attributes and limitations

This method has a high dynamic range thus making it suitable for sites where flow-rates can vary across a wide range. It is bi-directional enabling the measurement of reverse flows. This method is unaffected by the presence of particulate or air bubbles and, in a well designed system, there will be little or no obstruction to the flow.

On-site calibration will generally be required.

Local velocity sensors are usually streamlined to minimize fouling, but this can still occur, and in severe cases will lead to poor measurement. However, fouling is less of a problem than with ‘transit time’ ultrasonic or ultrasonic Doppler flow systems.

Spool piece sensors typically require five to ten times the internal diameter of the conduit of straight upstream pipework and three to five times the diameter downstream in order to minimize the effects of poor velocity profiles caused by bends and other sources of disturbance.

6.6.3 Equipment

The equipment required for this method comprises: one or more electromagnetic coils, power supply to drive the coils, means to detect the induced voltage, insulating liner, level sensor to measure fluid depth and a flow computer capable of taking the signals and combining them with a calibration curve to derive flow. In a spool piece sensor, the measurement parts are typically incorporated into one unit with the power supply, detection circuitry and flow computer in a second unit.

6.6.4 Application

Use of full-channel-width coils can be applied to very large conduits and channels up to 25 m in width. In such cases, the coils required to generate the field are physically large and require significant power. Hence, these are permanent installations. Installation of full-channel-width coils may require the temporary diversion of flow.

Local velocity sensors may be applied to filled or partially filled, round, rectangular, egg or other shaped conduits of 150 mm to 3 500 mm. They may be used for permanent or temporary installations.

Spool piece sensors typically start at 150 mm nominal bore. Manufacturers list models up to 800 mm nominal bore with larger sizes fabricated to order.

6.6.5 Uncertainties

For installations where a single coil spanning the channel is used, ISO 9213 claims uncertainties (with a coverage factor of 2 and an approximate confidence level of 95 %) in the range 2 % to 5 %. However, this may be limited by the calibration method rather than the performance of the flow meter itself. For installations where local velocity sensors are used, uncertainties are likely to be in the range 5 % to 10 %. For spool piece sensors, uncertainties on volumetric flow of 5 % and better are claimed, depending on the measurement range.

6.7 Slope-area method

6.7.1 Basic principles

The slope-area method is a means of determining discharge in open channels from observations of the surface slope and cross-sectional area of the channel. The mean velocity is established by using one of several well known empirical formulae. These formulae relate the velocity to the hydraulic radius, the energy gradient (surface water slope corrected for the kinetic energy of the flowing water) and a roughness coefficient that is a function of the characteristics of the channel bed and sides material. The technique is described in detail in ISO 1070.

One of the most commonly used formulae is that of Manning (see Equation [2]).

$$v = \frac{1}{n} R^{2/3} S^{1/2} \qquad [2]$$

where

v is the average velocity, in metres per second (m/s);

R is the hydraulic radius, in metres (m); $R = \frac{A}{P}$.

A is the cross-sectional area;

P is the wetted perimeter;

S is the slope of the energy line;

n is Manning's n (roughness coefficient).

The Colebrook-White equation [Equation (3)] for pipeflow can be utilized for use in open channel flow estimation.

$$\nu = -\left(\sqrt{32 g R^{2/3} S}\right) \log_{10}\left[\frac{k}{14{,}8R} + \frac{1{,}255\nu}{R\left(\sqrt{32 g R S}\right)}\right] \qquad [3]$$

where

k is the roughness height;

ν is the kinematic viscosity.

The main advantage of the slope-area method is that only water level measurement is required. If the energy and conduit bed gradients are identical then only one measurement is required. However, two water level measurements are preferred. Whenever possible, the length of the measuring reach should be such that the difference between the water levels at the upstream and downstream sensors should not be less than twenty times the uncertainty in the measurement.

Ideally, the conduit should be straight, there should be no abrupt changes in bed gradient, the cross section should be uniform and free from obstructions, and the conduit roughness should be uniform along the conduit reach.

6.7.2 Attributes and limitations

The method is often easy to set up and is relatively low cost. However, it is not as accurate as other methods and it is dependent on the assumed roughness coefficient. In some situations, it may be possible to determine the roughness coefficient using another flow measurement method, e.g. current meter gauging.

6.7.3 Equipment

Equipment suitable for the measurement of water levels in open channels is described in ISO 4373, to which reference should be made. The selection of a suitable water level sensor will be dependent on site conditions. The comments on water level monitoring equipment relating to structures (see 6.3.5) also apply to the slope-area method.

6.7.4 Applications

This method is applicable in long, straight conduits where other methods of flow measurement are not viable or where a quick spot flow estimate is required. The technique is often used for post-event flood peak flow estimation.

6.7.5 Uncertainties

The uncertainty in the determination of flow is a function of physical conditions and how well the roughness coefficient has been estimated. As already stated, the slope-area method is not as accurate as other methods of flow determination. However, in closed conduits, provided the hydraulic conditions are acceptable, it should be generally possible to estimate the discharge to an uncertainty (with a coverage factor of 2 and an approximate confidence level of 95 %) of within 20 %.

6.8 Non-contact methods

6.8.1 Basic principles

6.8.1.1 General

The fluid velocity and depth are measured independently by non-contact means and combined in a flow computer to give volumetric flow. Non-contact methods of fluid velocity measurement include radar and optical methods.

6.8.1.2 Radar

In the radar method, an electromagnetic beam is directed at the fluid surface at an oblique angle. The scattered radiation is collected and its frequency compared with the frequency of transmission. The change in frequency (Doppler shift) is proportional to the velocity of the signal scatterers. In fluid flow, these would be small particles at or close to the fluid surface, or discontinuities on the surface. Algorithms derived from on-site calibration or theoretical models are used to convert the measured velocity to the mean fluid velocity over the cross section at the point of measurement.

6.8.1.3 Optical

There are a number of well-established optical techniques for flow measurement. These include laser Doppler methods, particle image velocimetry and laser particle velocimetry. Such methods have tended to be confined to the laboratory due to the complexity of the optics and signal processing required. Recent advances in these areas mean that the industrial application of such techniques is becoming feasible.

A method using cross-correlation has been used for sewer flow. Two optical detectors displaced at a known distance along the velocity direction are focussed on two areas of the flow field. Each records a time series of the surface perturbations caused by surface turbulence or particulate. The two time series are cross-correlated and the time shift which gives the maximum correlation gives the travel time between the two sensors, hence the surface velocity.

6.8.2 Attributes and limitations

These are non-contact methods that do not present any obstruction to the flow. They are also not subject to fouling from the fluid and hence maintenance requirements should be minimal.

The relationship between the velocity measured at or near the surface to the mean fluid velocity may be difficult to derive.

As with other velocity-area methods, the relationship between fluid depth and cross-sectional area needs to be known. Also, surface effects such as standing waves and wind movement may seriously compromise the level of accuracy that can be achieved.

6.8.3 Equipment

To apply non-contact methods, two non-contact sensors are required – one for fluid velocity and a second for fluid depth. These may be combined in a single unit that also incorporates the flow computer required to process the measurements and derive flow.

6.8.4 Application

There is little restriction to the application of these methods and they may be used for permanent or temporary installations. They may be less suited to applications where the flow changes rapidly as they will typically take a number of individual readings from which an average reading will be obtained, thus update times (response times) can be slower than some other techniques.

6.8.5 Uncertainties

The uncertainty will depend upon how much the velocity distribution changes with water level and whether the relationship between surface velocity and mean velocity is consistent. Uncertainty (with a coverage factor of 2 and an approximate confidence level of 95 %) is unlikely to be better than 10 %, and could often be well in excess of this.

6.9 Spot flow measurements, evaluation and verification

If spot flow measurements are required for investigations or verification of another technique, then current meter gauging using either rotating element or electromagnetic or Doppler current meters may be an option. This will depend on the size and nature of the conduit.

Current meter gauging methods described in ISO 748 are applicable in closed conduits, but the following points should be noted.

a) The presence of particulate and fibrous matter will hinder the rotation of impeller and cup type meters. Also, for smaller conduits, say less than 300 mm width or diameter, these devices are often too bulky.

b) In conduits where the size of the meter in relation to the cross-sectional area of flow prevents the number of point measurements recommended being undertaken, it is sometimes assumed that the meter measures the mean velocity.

Where the use of a rotating element current meter is not possible due to high levels of suspended solids or other adverse physical conditions, an electromagnetic or ultrasonic Doppler current meter may offer an acceptable alternative. The design, selection and use of electromagnetic current meters are described in ISO/TS 15768. However, electromagnetic current meters are susceptible to interference from electrical noise. Therefore, steps should be taken to ensure that this is not a problem. Also, grease on the sensing head may have an effect on the device’s calibration by altering the electrical conducting properties of its electrodes.

7 Final selection of method

The final selection of a method will be dependent on a variety of factors, including health and safety considerations, the physical range of conditions, access, specific data requirements and budget availability (together with those factors discussed in Clause 5). The main methods of measurement and a guide to selection are summarized in Annex A.

Annex A
(informative)

Guide to the selection of methods

Guidance is given in Table A.1.

Table A.1 — Selection guide

Method	Long term [a]	Short term [b]	Spot measurement [c]	Minimum conduit width/ diameter	Minimum depth	Velocity	High suspended solids	Toxic or corrosive effluent	Cost	Labour intensive	Maintenance requirements	Calibration [d]	Uncertainty [e]
	Y/N	Y/N	Y/N	m	m	m/s	Y/N	Y/N	H/M/L	H/M/L	H/M/L	Y/N/PC	(± %)
Volumetric	Y [f]	Y	Y	nc	nc	nc	Y	Y	L	M	L	N	5
Dilution gauging	Y	Y	Y	nc	0,1	> 0,2	Y	Y	L to H [g]	L	L	N	5
Structures	Y	Y	Y?	0,3	0,03	[h]	Y [i]	Y?	H	L	H	PC	5 to 10
Ultrasonic Doppler	Y	Y	Y	0,3	0,1	+0,1	Y	Y?	M/L	M	M/L	Y/PC	10
Transit time ultrasonic	Y	Y	N	0,3	[j]	nc	Y/N	Y?	M	N	M/L	PC	5 to 10
Electromagnetic	Y	N	N	nc	?	nc	Y	Y?	H	N	L	Y/PC	5 to 10
Slope-area	Y	Y	Y	0,3	0,2	> 0,1	Y	Y	L	M	L	Y/PC	20
Non-contact methods	Y	Y	Y	0,3	0,1	> 0,3	Y	Y	H/M	M	L	Y	10 to 20
Current meters [k]	N	N	Y	0,1	0,05	> 0,03 [l]	Y/N [m]	N	L	H	L	N	10

Key

Y = yes; N = no; Y? = possibly, depends on conditions; H = high; M = medium; L = low;

PC = performance checking required; Calib. = calibration; nc = no significant constraint for most typical conduits; d = depth.

Table A.1 (*continued*)

[a] Continuous long-term monitoring – permanent installations.

[b] Short-term continuous monitoring – temporary installations.

[c] Spot flow measurements i.e. single, instantaneous or quasi-instantaneous measurements.

[d] Does the method require calibrating or performance checking by one of the other methods.

[e] The uncertainties are those that can be achieved provided the hydraulic conditions and other physical conditions are suitable for the successful application of the method. Uncertainties have an approximate confidence level of 95 %.

[f] Only if suitable volumetric tanks are installed in the drainage system.

[g] The cost depends on the type of system used, for instance a continuous monitoring radioactive tracer system can have a high cost, whereas a gulp injection system using salt as the tracer can be low cost.

[h] For most structures, Froude numbers, $Fr = \frac{v}{\sqrt{gd}}$, in the approach section should not exceed 0,5.

[i] Some structures are better at coping with high levels of suspended solids than others.

[j] The depth required can be estimated from $d = 54\sqrt{\frac{L}{f}}$ where d = depth (in metres, m), L = path length (in metres, m), f = transducer frequency (in hertz, Hz).

[k] It may be difficult to meet the requirements for safe systems of work in confined spaces.

[l] Electromagnetic current meters may be used at lower velocities but the uncertainties will be greater.

[m] For electromagnetic current meters: yes; for rotating element current meters: no.

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