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Measurement of liquid flow in open channels — Parshall and SANIIRI flumes

Mesure de débit des liquides dans les canaux découverts — Canaux jaugeurs Parshall et SANIIRI

INTERNATIONAL ISO

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Foreword

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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.

International Standard ISO 9826 was prepared by Technical Committee ISO/TC 113, *Measurement of liquid flow in open channels*, Sub-Committee SC 2, *Notches, weirs and flumes*.

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Measurement of liquid flow in open channels — Parshall and SANIIRI flumes

1 Scope

This International Standard specifies methods of liquid flow measurement in open channels (particularly in irrigation canals) under steady or slowly varying flow conditions, using Parshall and SANIIRI flumes.

These flumes are designed to operate under both free-flow and submergence conditions.

2 Normative reference

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

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

3 Definitions and symbols

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

3.1 Parshall flume: Measuring flume having a converging entrance section with a level floor, a short throat section with a floor inclined downwards at a gradient of 3:8, and a diverging exit section with a floor inclined upwards at a gradient of 1:6.

3.2 SANIIRI flume: Measuring flume with a converging entrance section having a level floor with a vertical drop at its downstream end and perpendicular walls to join it to the downstream channel.

4 Selection of flume type

4.1 The choice as to whether a Parshall or a SANIIRI flume should be used depends on several factors such as the range of discharge to be measured, the head available, the modular limit and the maximum submergence ratio, the channel or canal characteristics, the amount of head loss which can be allowed through the flume, the possibility of deepening the bed and providing a drop therein, the accuracy of measurement required, whether or not the flow carries sediment, the operating conditions that necessitate the use of either stationary or portable flumes, and economic considerations.

4.2 Parshall flumes have a rectangular cross-section and a wide range of throat widths varying from very small (0,025 4 m) to large (15 m and greater).

Medium-sized Parshall flumes, with throat widths between about 0,15 m and about 2,5m, which are suitable for measuring discharges in the range from 0,001 5 m^3/s to 4,0 m^3/s are those most commonly used for flow measurements; they are thus recommended in this International Standard as "standard structures".

Large Parshall flumes with throat widths between about 3 m and about 15 m, the design of which varies depending on the size of the flume, are suitable for measuring discharges in the range from 0,75 m^3/s to 93 m^3/s.

One of the most desirable features of the Parshall flume is that it operates satisfactorily at high submergence ratios with low head loss, this makes it especially suitable for flow measurements in channels having small bed slopes. However, the complicated design of this flume (see figure 1) offsets somewhat the advantages that it offers.

4.3 SANIIRI flumes are rectangular in cross-section, level-floored and have an exit cross-sectional width between 0,3 m and 1,0 m. They are suitable for measuring discharges in the range from 0,03 m^3/s and 2,0 m^3/s.

SANIIRI flumes are simple in design and construction, with the exception that a small fall at the downstream end of the floor (see figure 3) of the flume has to be provided.

5 Installation

5.1 Selection of site

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

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

a) the adequacy of the length of channel of regular cross-section and slope available;

b) the uniformity of the existing velocity distribution;

c) the conditions downstream (including influences such as tides, control structures, etc.);

d) 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;

e) the stability of the banks or side slopes of the channel, and the necessity for trimming and/or revetment;

f) the necessity for flood banks, to confine the maximum discharge to the channel and the backwater caused by the installation of the flume;

g) the effect of wind on the flow over the flume, especially when the flume is wide and the head is small and when the prevailing wind is in a direction transverse to the direction of flow;

h) aquatic weed growth;

i) sediment transported by the flow.

5.1.3 If the site does not possess the characteristics necessary for satisfactory discharge measurements, it shall not be used unless suitable improvements are practicable.

5.2 Installation conditions

5.2.1 General requirements

The complete measuring installation consists 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. In addition, features such as the surface finish of the flume, the cross-sectional shape of the channel and the channel roughness shall be taken into consideration.

5.2.2 Approach channel

5.2.2.1 The approach channel shall comply with the following requirements.

a) It shall be straight and uniform and have a constant slope for a length equal to five to ten times the water surface width at maximum flow.

b) The bed slope shall be such as to ensure subcritical flow with a Froude number Fr of less than 0,5 (or 0,7), where:

$$Fr = \frac{Q_{max}}{A\sqrt{gh_{max}}}$$

where

Q_{max} is the maximum discharge;

A is the cross-sectional area of the channel;

h_{max} is the maximum water depth.

5.2.2.2 The flow conditions and the symmetry of the velocity distribution in the approach channel shall be checked by inspection and measurement using, for example, current-meters, floats, velocity rods or dye.

NOTE 1 A complete assessment of the velocity distribution may be made by using a current-meter.

5.2.3 Flume structure

5.2.3.1 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 in the upstream channel, and the geometry shall conform with the dimensions given in clause 8 or clause 9 as appropriate.

5.2.3.2 The surfaces of the flume, particularly those of the entrance section and throat, shall be smooth. The flume may be constructed of concrete with a smooth cement finish or may be surfaced with a smooth non-corrodible material. In laboratory installations, the finish shall be equivalent to that of rolled sheet metal or planed, sanded and painted timber. The surface finish is of particular importance within the prismatic part of the throat, but the requirements may be relaxed beyond a distance along the profile $0{,}5h_{max}$ upstream and downstream of the throat proper.

5.2.3.3 To minimize uncertainty in the discharge measurement, the following tolerances shall be satisfied in construction:

a) on the bottom width b of the throat: 0,2 % of b with an absolute maximum of 0,01 m;

b) on point deviations from a plane surface 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 the slope of inclined surfaces in the throat: 0,1 %;

f) on the length of the throat: 1 % of l;

g) on point deviations from a plane surface in the entrance transition to the throat: 0,1 % of l;

h) on point deviations from a plane surface in the exit transition from the throat: 0,3 % of l;

i) on deviations from a plane or curve on other vertical or inclined surfaces: 1 %;

j) on deviation from a plane of the bed of the lined approach channel: 0,1 % of l.

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

5.2.4 Downstream of the structure

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 normal operating conditions except for a limited period of time, e.g. during floods. The construction of a flume in a river or stream may alter the flow conditions upstream and downstream of the structure. This may result in the accumulation of river bed material further downstream which, in time, may cause the normal water level to rise sufficiently to drown the flume, particularly at low rates of flow. Any such accumulation of material shall be removed before it becomes excessive.

6 Maintenance — General requirements

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

It is essential that, as far as practicable, the approach channel to flumes be kept clean and free from silt and vegetation for the minimum distance specified in 5.2.2.1.

6.2 The float well, the connecting pipe and the inlet from the approach channel shall 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.

7 Measurement of head(s)

General methods and devices for measurement of head(s), and details of the design and functional requirements of stilling wells and details of the zero setting of a water-level measuring device are specified in ISO 4373. Requirements on head measurements for particular types of flume are dealt with in clauses 8 and 9 .

8 Parshall flumes

8.1 Description

Parshall flumes have a rectangular cross-section and consist of a converging entrance section, a throat and a diverging exit section (see figure 1).

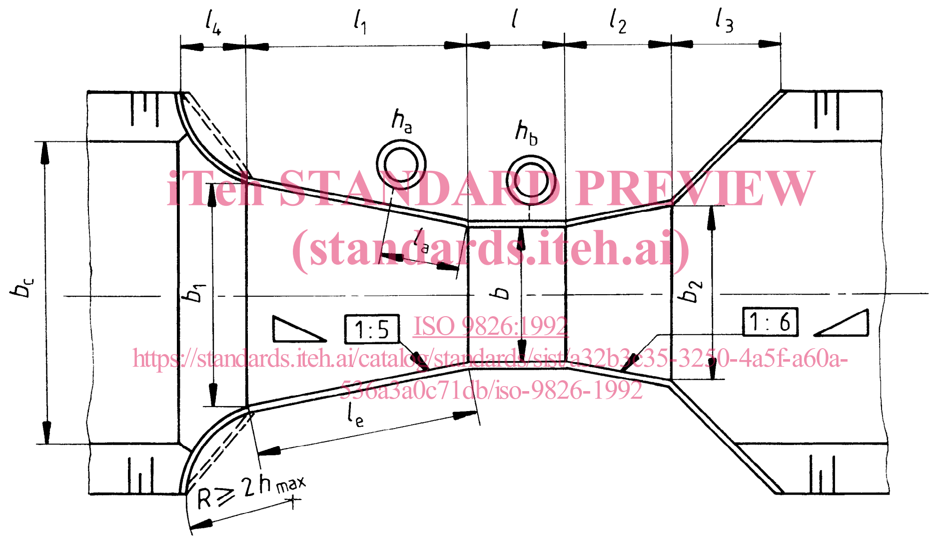
The floor of the entrance section shall be truly level both longitudinally and laterally. The side walls shall be vertical and disposed at a constant angle of convergence of 11° 19′ or shall have a 1:5 contraction in plan with respect to the flume axis.

The side walls of the throat shall be parallel in plan. The floor shall be inclined downwards with a gradient of 3:8; this applies to flumes of all sizes. The line of intersection of the entrance section floor with the throat floor is known as the crest of the flume. The elevation of the crest above the throat invert is referred to as the height of the flume crest h_{p1}.

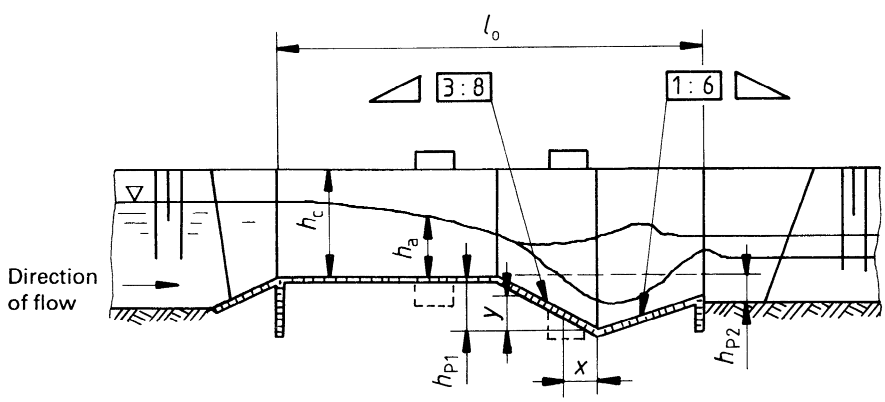
The side walls of the exit section shall be vertical and disposed at a constant angle of divergence of 9° 28′ or shall have a 1:6 expansion in plan with respect to the flume axis. The floor shall be inclined upwards with a reverse gradient of 1:6; this applies to flumes of all sizes.

To ensure a smooth entry of the flow into the flume and to prevent surface disturbance at the exit of the flume, the entrance and exit cross-sections shall be connected to the natural channel banks or the artificial channel side slopes by means of vertical wing walls disposed at 45° to the flume axis or curved in plan with a radius $R \geqslant 2h_{max}$ (see figure 1). For smaller sizes of flumes with throat widths less than 0,5 m, the wing walls may be placed at right angles to the flume axis.

Parshall flumes may be constructed of wood, stone, concrete, reinforced concrete, or any other material depending on the prevailing conditions. Small Parshall flumes may be built of sheet metal and used as portable structures. Flumes made of reinforced concrete may be prefabricated for assembly in the field.



a) Plan view



b) Sectional view

Figure 1 — Parshall flume

Table 1 — Dimensions for standard Parshall flumes

Dimensions in metres

Parshall flume No.	Throat					Entrance section				Exit section			Side wall height
	b	l	X	Y	h_{p1}	b_1	l_1	l_e	l_a	b_2	l_2	h_{p2}	h_c
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	0,152	0,305	0,05	0,075	0,115	0,40	0,610	0,622	0,415	0,39	0,61	0,012	0,60
2	0,250	0,600	0,05	0,075	0,230	0,78	1,325	1,352	0,900	0,55	0,92	0,072	0,80
3	0,300	0,600	0,05	0,075	0,230	0,84	1,350	1,377	0,920	0,60	0,92	0,072	0,95
4	0,450	0,600	0,05	0,075	0,230	1,02	1,425	1,454	0,967	0,75	0,92	0,072	0,95
5	0,600	0,600	0,05	0,075	0,230	1,20	1,500	1,530	1,020	0,90	0,92	0,072	0,95
6	0,750	0,600	0,05	0,075	0,230	1,38	1,575	1,607	1,074	1,05	0,92	0,072	0,95
7	0,900	0,600	0,05	0,075	0,230	1,56	1,650	1,683	1,121	1,20	0,92	0,072	0,95
8	1,000	0,600	0,05	0,075	0,230	1,68	1,700	1,734	1,161	1,30	0,92	0,072	1,00
9	1,200	0,600	0,05	0,075	0,230	1,92	1,800	1,836	1,227	1,50	0,92	0,072	1,00
10	1,500	0,600	0,05	0,075	0,230	2,28	1,950	1,989	1,329	1,80	0,92	0,072	1,00
11	1,800	0,600	0,05	0,075	0,230	2,64	2,100	2,142	1,427	2,10	0,92	0,072	1,00
12	2,100	0,600	0,05	0,075	0,230	3,00	2,250	2,295	1,534	2,40	0,92	0,072	1,00
13	2,400	0,600	0,05	0,075	0,230	3,36	2,400	2,448	1,632	2,70	0,92	0,072	1,00

8.2 Dimensions

Parshall flumes have a specific feature in that the flumes are not geometrically similar models of each other. The throat length, crest height and length of the exit section remain constant for a series of flumes while other dimensions vary as a function of the throat width; these other dimensions may be determined analytically.

It is thus essential to use calibrated flumes constructed in accordance with the dimensions specified in tables 1 and 2 for standard and large Parshall flumes respectively.

8.2.1 Standard Parshall flumes

The size of a particular standard Parshall flume is denoted by its throat width b (see table 1, column 2).

For the series of standard Parshall flumes having throat widths b from 0,250 m to 2,400 m (see table 1, column 1, Nos. 2 to 13) the leading dimensions are identical, i.e. the throat length l (column 3), the height of the crest h_{p1} (column 6), the coordinates X and Y of the throat cross-section at the stilling well pipe used for the measurement of the head h_b (columns 4 and 5), the axial length of the exit section l_2 (column 12), the height h_{p2} (column 13), the slope of the throat floor (3:8) and the reverse slope of the exit section floor (1:6).

The other dimensions of these flumes (Nos 2 to 13) are calculated using the following equations.

a) Width, in metres, of the entrance cross-section of the flume

$$b_1 = 1{,}2b + 0{,}48 \qquad \ldots (1)$$

b) Axial length, in metres, of the entrance section

$$l_1 = 0{,}5b + 1{,}2 \qquad \ldots (2)$$

c) Converging wall length, in metres

$$l_e = 1{,}02 l_1 \qquad \ldots (3)$$

d) Wall length, in metres, between the crest and the head h_a measurement section

$$l_a = 2l_e/3 \qquad \ldots (4)$$

e) Width, in metres, of the exit cross-section of the flume

$$b_2 = b + 0{,}30 \qquad \ldots (5)$$

f) Side wall height, in metres, in entrance section

$$h_c = h_{a,\,\max} + (0{,}15 \text{ à } 0{,}20) \qquad \ldots (6)$$

It is recommended that an additional allowance of up to 1 m be provided in the height of the side walls to avoid the risk of overtopping when flows through the flume are in excess of the maximum design discharge.

The lengths l_3 and l_4 of the wing walls vary with the width of the natural or artificial channel (see figure 1). To ensure proper connection to the channel banks or the artificial channel side slopes, the wing walls shall extend a distance of at least 0,4 m to 0,5 m into the channel banks.

8.2.2 Large Parshall flumes

In contrast with standard Parshall flumes, the dimensions of large Parshall flumes shall be determined independently for each particular design as a function of the throat width. No analytical equations are available for the determination of the leading dimensions of large Parshall flumes; the values specified in table 2 shall apply. These values shall be neither varied nor rounded off without additional calibration of the flume.

Table 2 gives the leading dimensions of large Parshall flumes with throat widths between 3,05 m and 15,24 m for measuring discharges in the range from 0,16 m^3/s to 93 m^3/s. It may be seen in table 2 that l, X, Y, h_{p1} and h_{p2} remain constant for a series of flumes. In addition, the slopes 3:8 and 1:6 of the throat floor and the exit section floor respectively, and the angles of convergence (11° 19′) and divergence (9° 28′) of the side walls of the entrance and exit sections also remain constant for all Parshall flumes. The only dimension that may be determined analytically is the wall length between the crest and the entrance cross-section of the stilling well pipe used for the measurement of h_a.

This length is given, in metres, by the equation

$$l_a = \frac{b}{3} + 0,813 \qquad \ldots (7)$$

It is recommended that the throat width b be equal to from one-third to one-half times the bottom width b_c of the natural or artificial channel (see figure 1).

Table 2 — Dimensions for large Parshall flumes

Dimensions in metres

Parshall flume No.	Throat					Entrance section			Exit section			Side wall height
	b	l	X	Y	h_{p1}	b_1	l_1	l_a	b_2	l_2	h_{p2}	h_c
1	2	3	4	5	6	7	8	9	10	11	12	13
14	3,05	0,91	0,305	0,23	0,343	4,76	4,27	1,83	3,66	1,83	0,152	1,22
15	3,66	0,91	0,305	0,23	0,343	5,61	4,88	2,03	4,47	2,44	0,152	1,52
16	4,57	1,22	0,305	0,23	0,457	7,62	7,62	2,34	5,59	3,05	0,203	1,83
17	6,10	1,83	0,305	0,23	0,686	9,14	7,62	2,84	7,32	3,66	0,305	2,13
18	7,62	1,83	0,305	0,23	0,686	10,67	7,62	3,35	8,94	3,96	0,305	2,13
19	9,14	1,83	0,305	0,23	0,686	12,31	7,93	3,86	10,57	4,27	0,305	2,13
20	12,19	1,83	0,305	0,23	0,686	15,48	8,23	4,88	13,82	4,88	0,305	2,13
21	15,24	1,83	0,305	0,23	0,686	18,53	8,23	5,89	17,27	6,10	0,305	2,13

8.3 Measurement of head and limits of application

The discharge through a Parshall flume is determined by measuring the heads in the entrance section (upstream head, h_a) and throat section (downstream head, h_b). Whether one or both heads have to be measured depends on the flow conditions in the flume.

For free-flow conditions, only the head h_a needs to be measured. The section for measurement of the head h_a shall be located a distance l_a measured along the oblique wall upstream from the crest of the flume [l_a may be calculated using formula (4) and formula (7)]. The recommended range of heads h_a is specified in tables 3 and 4.

Where high accuracy is not of great importance a staff gauge, set vertically in the head measurement section on the inside face of the converging entrance wall, may be used to determine the head h_a. The staff gauge shall be zeroed carefully with respect to the elevation of the flume crest, which is the elevation of the horizontal flume floor at the downstream end of the entrance section.

Table 3 — Discharge characteristics of standard Parshall flumes

Parshall flume No.	Throat width b m	Discharge equation[1)] $Q = Ch_a^n$ m^3/s	Head range h_a m min.	Head range h_a m max.	Discharge range[2)] Q $\times 10^{-3}$ m^3/s min.	Discharge range[2)] Q $\times 10^{-3}$ m^3/s max.	Modular limit σ_c (experimental)	Submergence ratio σ (recommended)
1	2	3	4	5	6	7	8	9
1	0,152	$0,381\ h_a^{1,580}$	0,03	0,45	1,5	100	0,55	0,6
2	0,25	$0,561\ h_a^{1,513}$	0,03	0,60	3,0	250	—	0,6
3	0,30	$0,679\ h_a^{1,521}$	0,03	0,75	3,5	400	0,62	0,6
4	0,45	$1,038\ h_a^{1,537}$	0,03	0,75	4,5	630	0,64	0,6
5	0,60	$1,403\ h_a^{1,548}$	0,05	0,75	12,5	850	0,66	0,6
6	0,75	$1,772\ h_a^{1,557}$	0,06	0,75	25,0	1 100	0,67	0,6
7	0,90	$2,147\ h_a^{1,565}$	0,06	0,75	30,0	1 250	0,68	0,6
8	1,00	$2,397\ h_a^{1,569}$	0,06	0,80	30,0	1 500	—	0,7
9	1,20	$2,904\ h_a^{1,577}$	0,06	0,80	35,0	2 000	0,70	0,7
10	1,50	$3,668\ h_a^{1,586}$	0,06	0,80	45,0	2 500	0,72	0,7
11	1,80	$4,440\ h_a^{1,593}$	0,08	0,80	80,0	3 000	0,74	0,7
12	2,10	$5,222\ h_a^{1,599}$	0,08	0,80	95,0	3 600	0,76	0,7
13	2,40	$6,004\ h_a^{1,605}$	0,08	0,80	100,0	4 000	0,78	0,7

1) $C = C_D b \times 3,279^n$

where

C_D is the coefficient of discharge;

n is an exponent dependent on b.

2) Rounded to the nearest rationalized value.

Table 4 — Discharge characteristics of large Parshall flumes

Parshall flume No.	Throat width b m	Discharge equation[1)] for free-flow conditions $Q = C_1 h_a^{1,8}$ m³/s	Head range h_a m min.	Head range h_a m max	Discharge range Q m³/s min.	Discharge range Q m³/s max.	Submergence ratio σ (recommended)	Submergence coefficient (correction factor) C_a
1	2	3	4	5	6	7	8	9
14	3,05	$7,463\ h_a^{1,6}$	0,09	1,07	0,16	8,28	0,80	1,0
15	3,66	$8,859\ h_a^{1,6}$	0,09	1,37	0,19	14,68	0,80	1,2
16	4,57	$10,96\ h_a^{1,6}$	0,09	1,67	0,23	25,04	0,80	1,5
17	6,10	$14,45\ h_a^{1,6}$	0,09	1,83	0,31	37,97	0,80	2,0
18	7,62	$17,94\ h_a^{1,6}$	0,09	1,83	0,38	47,16	0,80	2,5
19	9,14	$21,44\ h_a$	0,09	1,83	0,46	56,33	0,80	3,0
20	12,19	$28,43\ h_a^{1,6}$	0,09	1,83	0,60	74,70	0,80	4,0
21	15,24	$35,41\ h_a^{1,6}$	0,09	1,83	0,75	93,04	0,80	5,0

1) $C_1 = C_D b$, where C_D is the coefficient of discharge.

Where greater accuracy is required or where continuous-recording instruments or stage-sensing devices are to be used, consideration shall be given to providing a stilling well. To connect the stilling well to the flow in the flume, a length of pipe is used, its inlet being located at the recommended position for the measurement of head, near the floor of the entrance section (see figure 1).

If a Parshall flume is to be operated under submerged-flow conditions, measurement of both heads h_a and h_b is required. The section for the measurement of h_b shall be located in the throat, a distance X from the throat invert. Since the flow in the throat is quite turbulent, which causes considerable fluctuation of the water surface, it is undesirable to use a staff gauge for the measurement of h_b. Consequently, a stilling well is necessary.

Tables 1 and 2 give values of X and Y, which are the coordinates of the entrance cross-section of the connecting pipe, for various flume sizes. The stilling well may accommodate a staff gauge, a stage-sensing device or a continuous-recording instrument which shall be zeroed accurately to the elevation of the flume crest.

The design of stilling wells and connecting pipes shall comply with the requirements specified in clause 7.

Stilling wells for the measurement of heads h_a and h_b shall preferably be placed adjacent to one another so that the complete installation is located in one place (either outdoors or indoors).

The recommended range of heads that can be measured by various sizes of Parshall flumes is from 0,03 m to 0,8 m for standard flumes and from 0,09 m to 1,83 m for large flumes (see tables 3 and 4 respectively).

8.4 Free-flow and submerged-flow conditions

The discharge through a Parshall flume is considered to be free flow when it is independent of variations in tail-water level. In a Parshall flume operating under free-flow conditions, flow in the entrance section is subcritical, with depths decreasing in the direction of flow until the critical depth is reached near the flume crest. Beyond the crest, in the throat section, depths are subcritical (see figure 1). Free-flow conditions will exist until the downstream head increases to the point where it causes the submergence ratio ($\sigma = h_b/h_a$) to become equal to the modular limit σ_c, i.e.

$$\sigma_c = h_b/h_a \qquad \ldots (8)$$

When this happens the flow in the exit section and in the greater part of the throat becomes drowned (see figure 1).

With an even greater downstream head, submerged-flow conditions will extend further upstream to the entrance section and will thereby reduce the discharge through the flume. In a flume operating under submerged-flow conditions, the discharge to be measured depends on the submerged ratio σ.

Calibration tests indicate the modular limit for standard Parshall flumes to be from 0,55 to 0,78 (see table 3, column 8). The recommended average value of the submergence ratio is 0,6 to 0,7 (see table 3, column 9) and 0,8 (see table 4, column 8) for standard and large Parshall flumes respectively.

The determination of discharge under submerged-flow conditions is possible provided that the submergence ratio does not exceed 0,95.

With higher submergence ratios the flume ceases to operate as a flow-measuring structure.

It should be noted that a flume operating under submerged-flow conditions offers the advantage of the lowest head loss. However, submerged flow conditions make discharge measurements less accurate than those carried out under free-flow conditions. It is thus advisable to choose the dimensions of a flume so that it operates under submerged-flow conditions only for a limited period of time, e.g. during floods.

8.5 Determination of discharge

8.5.1 Determination of discharge under free-flow conditions

The discharge through a Parshall flume operating under free-flow conditions (i.e. $\sigma < \sigma_c$) is obtained from the following general equation:

$$Q = C_D b h_a^n \qquad \ldots (9)$$

where

Q is the discharge, in cubic metres per second;

b is the throat width, in metres;

h_a is the head in the entrance section, in metres;

C_D is the coefficient of discharge;

n is an exponent dependent on b.

The discharge through standard Parshall flume Nos. 2 to 13, operating under free-flow conditions, is obtained from the following equation:

$$Q = 0{,}372 b \left(\frac{h_a}{0{,}305} \right)^{1{,}569 b^{0{,}026}} \qquad \ldots (10)$$

(i.e. $C_D = 0{,}372$ and $n = 1{,}569 b^{0{,}026}$; for the standard Parshall flume No. 1, $C_D = 0{,}384$ and n has the same values as above).

The discharge equations for each of the standard Parshall flumes are specified in table 3, column 3, where $C = C_D b (3{,}279)^n$.

The discharge through large Parshall flumes (see table 4, column 1, Nos. 14 to 21) operating under free-flow conditions (i.e. $\sigma < \sigma_c$) is obtained from the following equation:

$$Q = (2{,}292 b + 0{,}48) h_a^{1{,}6}$$
$$\approx (2{,}3 b + 0{,}48) h_a^{1{,}6} \qquad \ldots (11)$$

(i.e. $C_D = 2{,}3 + 0{,}48/b$ and $n = 1{,}6$.)

The discharge equations for each of the large Parshall flumes are specified in table 4, column 3, where $C_1 = C_D b$.

Tables 3 and 4 also give values of the range of free discharge [computed from formulae (10) and (11)] applicable for all flume sizes.

8.5.2 Determination of discharge under submerged-flow conditions

The discharge through a Parshall flume operating under submerged-flow conditions is affected by the downstream head and is thus obtained by means of an adjustment to the free discharge:

$$Q_{dr} = Q - Q_E \qquad \ldots (12)$$

where

Q_{dr} is the submerged discharge;

Q is the free discharge obtained from either formula (10) or formula (11);

Q_E is the reduction in discharge as a result of submergence.