IS : 11625 - 1986
(Reaffirmed 2001)

Indian Standard

CRITERIA FOR HYDRAULIC DESIGN OF PENSTOCKS

UDC 627·844 : 624 ·04

INDIAN STANDARDS INSTITUTION
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

Gr 4 *November* 1986

Indian Standard

CRITERIA FOR HYDRAULIC DESIGN OF PENSTOCKS

Water Conductor Systems Sectional Committee, BDC 58

Chairman
SHRI P. M. MANE
39, Shivaji Co-operative Housing Society, Pune

Members	*Representing*
CHIEF ENGINEER	Mukerian Hydel Project Design, Chandigarh
DIRECTOR (*Alternate*)	
CHIEF ENGINEER (HP)	Tamil Nadu Electricity Board, Coimbatore
SUPERINTENDING ENGINEER (*Alternate*)	
CHIEF ENGINEER (GENERAL)	Public Works Department, Government of Tamil Nadu, Madras
CHIEF ENGINEER (IRRIGATION) (*Alternate*)	
CHIEF ENGINEER (CIVIL DESIGNS)	Karnataka Power Corporation Limited, Bangalore
SHRI P. R. MALLIKARJUNA (*Alternate*)	
CHIEF ENGINEER	Bhakra Beas Management Board, Chandigarh
SHRI SUNDERSHAN KUMAR (*Alternate*)	
CHIEF ENGINEER (IRRIGATION SOUTH)	Public Works and Electricity Department, Government of Karnataka, Mysore
SUPERINTENDING ENGINEER (*Alternate*)	
SHRI C. ETTY DARWIN	In personal capacity (*P. O. Muttada, Trivandrum*)
DIRECTOR	Central Soils and Materials Research Station, New Delhi
DEPUTY DIRECTOR (*Alternate*)	
DIRECTOR (HCD-I)	Central Water Commission, New Delhi
DEPUTY DIRECTOR (HCD-I) (*Alternate*)	
DR A. K. DUBE	Central Mining Research Station Unit, Roorkee
DR J. L. JETHWA (*Alternate*)	
DR B. PANT	Water Resources Development Training Centre, Roorkee
SHRI J. P. GUPTA	Power House Designs, Irrigation Department, Roorkee
SHRI A. P. GUPTA (*Alternate*)	
SHRI M. V. S. IYENGAR	Hindustan Construction Co Ltd, New Delhi
SHRI M. G. KHAN (*Alternate*)	

(*Continued on page* 2)

(*Continued from page* 1)

Members	*Representing*
JOINT DIRECTOR RESEARCH (GE-II)	Research Designs and Standards Organization, Lucknow
SHRI P. N. KHAR	National Hydroelectro Power Corporation Ltd, New Delhi
SHRI A. K. MEHTA	National Projects Construction Corporation Limited, New Delhi
SHRI S. C. BALI (*Alternate*)	
MEMBER (CIVIL)	Kerala State Electricity Board, Trivandrum
SHRI G. PANT	Geological Survey of India, New Delhi
SHRI N. K. MANDWAL (*Alternate*)	
SHRI A. R. RAICHUR	In personal capacity (*147, Garodianagar, Bombay*)
SHRI Y. RAMA KRISHNA RAO	Andhra Pradesh State Electricity Board, Hyderabad
SUPERINTENDING ENGINEER (DESIGN AND PLANNING) (*Alternate*)	
SHRI G. V. SATHAYE	Central Designs Organization, Nasik
DR H. R. SHARMA*	Central Electricity Authority, New Delhi
SHRI S. C. SEN	Assam State Electricity Board, Guwahati
SHRI N. K. DAS (*Alternate*)	
SHRI A. K. SRIKANTIAH	Himachal Pradesh State Electricity Board, Sundernagar
SHRI RANJODH SINGH (*Alternate*)	
REPRESENTATIVE	Central Water and Power Research Station, Pune
SHRI A. V. GOPALAKRISHNA (*Alternate*)	
SHRI G. RAMAN, Director (Civ Engg)	Director General, ISI (*Ex-officio Member*)

Secretary

SHRI HEMANT KUMAR
Deputy Director (Civ Engg), ISI

Panel for Penstocks and Anchor Blocks, BDC 58 : P6

Convener	*Representing*
KUMARI E. DIVATIA	National Hydroelectric Power Corporation Limited, New Delhi
Members	
SHRI M. L. AGGARWAL	Bhakra Beas Management Board, Chandigarh
SHRI Y. P. NAYAR (*Alternate*)	
DIRECTOR (HCD-I)	Central Water Commission, New Delhi
DEPUTY DIRECTOR (HCD) (*Alternate*)	
DIRECTOR (D&P)	Irrigation Works, Government of Punjab, Chandigarh
SENIOR DESIGN ENGINEER (*Alternate*)	

(*Continued on page* 15)

*Chairman for the meeting.

Indian Standard

CRITERIA FOR HYDRAULIC DESIGN OF PENSTOCKS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 28 February 1986, after the draft finalized by the Water Conductor System Sectional Committee had been approved by the Civil Engineering Division Council.

0.2 The water is taken from the forebary to the power station through the penstocks. These may be pressure conduits or shafts. The penstocks shall carry water to the turbines with the least possible loss of head consistent with the overall economy of the project. For successful operation, the size of the pipe for a given discharge may vary between wide limits, but there is usually one size that will make for the greatest economy and design. Hence the diameter of the penstocks is determined from the consideration of economy and is checked to see that the acceptable velocities are not exceeded.

1. SCOPE

1.1 This standard covers the criteria for hydraulic design of penstocks.

2. GENERAL

2.1 The hydraulic design of penstocks covers hydraulic design of intake for penstocks, hydraulic losses in penstock, pressure rise or pressure drop due to turbine or pump operations and ascertaining most economic diameter of penstock on the basis of available data.

3. HYDRAULIC DESIGN OF INTAKE FOR PENSTOCK

3.1 The hydraulic design of the main components of intake shall be in accordance with IS : 9761-1981*.

*Criteria for hydraulic design of hydropower intakes.

4. HYDRAULIC LOSSES IN PENSTOCK

4.1 The hydraulic losses in the penstock comprise the following:

a) Head loss at trash rack,
b) Head loss at intake entrance,
c) Friction losses, and
d) Other losses as at bends, bifurcations, transitions, valves, etc.

These head losses are expressed in terms of coefficient to be applied to the velocity head at the section in question.

4.2 Head Loss at Trash Rack

4.2.1 The head loss through trash rack (h_t) may be expressed by the formula given below:

$$h_t = k_t \frac{v^2}{2g}$$

where

h_t = trash rack head loss,
k_t = loss coefficient,
v = actual velocity through rack opening, and
g = acceleration due to gravity.

The loss coefficient k_t shall be calculated in accordance with IS : 4880 (Part 3)-1976*.

4.3 Head Loss at Intake Entrance

4.3.1 The magnitude of head loss at entrance depends upon the shape of intake mouth. For bell mouth shape shown in Fig. 1, losses are given by the following formula:

$$h_e = k_e \frac{v^2}{2g}$$

where

h_e = head loss at entrance,
k_e = loss coefficient at entrance,
v = velocity at entrance, and
g = acceleration due to gravity.

4.3.2 The value of loss coefficient k_e shall be in accordance with IS : 4880 (Part 3)-1976*.

*Code of practice for design of tunnels conveying water : Part 3 Hydraulic design (*first revision*).

4.4 Friction Losses

4.4.1 Head loss due to friction in pipes may be estimated from the formulae given in **4.4.1.1** to **4.4.1.2**.

4.4.1.1 Darcy-Waisbach formula:

$$h_f = \frac{f L v^2}{2gD}$$

where

h_f = friction head loss in pipe in m;

f = loss coefficient depending upon type, conditions of the pipe and Reynolds number which may be obtained from Fig. 2;

L = length of pipe in m;

v = velocity through pipe in m/sec; and

D = diameter of pipe.

4.4.1.2 Manning's formula may be used in case of fully rough turbulent flow.

Manning's formula

$$V = \frac{R^{2/3}\ S^{1/2}}{n}$$

where

R = hydraulic radius $\left(\frac{\text{area}}{\text{witted perimeter}}\right)$ in m;

S = slope of energy gradient; and

n = roughness coefficient, shall vary from 0·012 to 0·014 for concrete pipes and for steel pipes the valve of *n* shall vary from 0·008 to 0·012.

4.5 Other Losses

4.5.1 In a penstock other losses include losses due to bends, expansion or contraction, obstruction caused by valve passage and losses in penstock branches and wyes.

4.5.2 *Bend Loss* — The bend loss excluding friction loss for a circular conduit depends upon the shape of bend, deflection angle and ratio of radius of bend to diameter of pipe. The bend loss may be calculated from the following formula:

$$h_b = k_b \frac{v^2}{2\,g}$$

where

h_b = head loss due to bend,

k_b = bend loss coefficient which may be obtained from Fig. 3 for various R/D ratios and deflection angles, and

v = velocity in pipe.

4.5.3 *Loss Due to Expansion and Contraction*

4.5.3.1 Head loss due to gradual expansion h_{ex} may be estimated from the formula:

$$h_{ex} = \frac{k_{ex}\,(V_1 - V_2)^2}{2\,g}$$

where

V_1 = velocity at upstream end in m/sec;

V_2 = velocity at downstream end in m/sec, and

k_{ex} = loss coefficient depending upon the cone angle and shall be in accordance with IS : 2951 (Part 2) - 1965*.

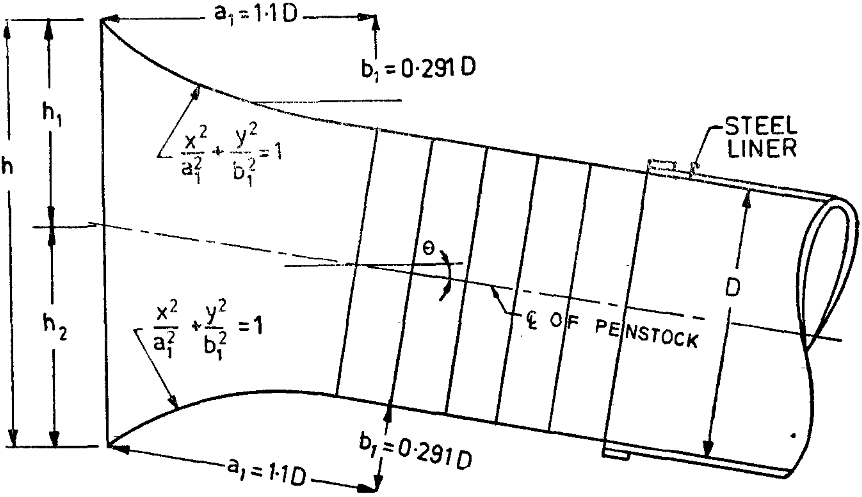

FIG. 1A BELL MOUTH DETAILS — *Contd*

*Recommendations for estimation of flow of liquids in closed conduits : Part 2 Head loss in valves and fittings.

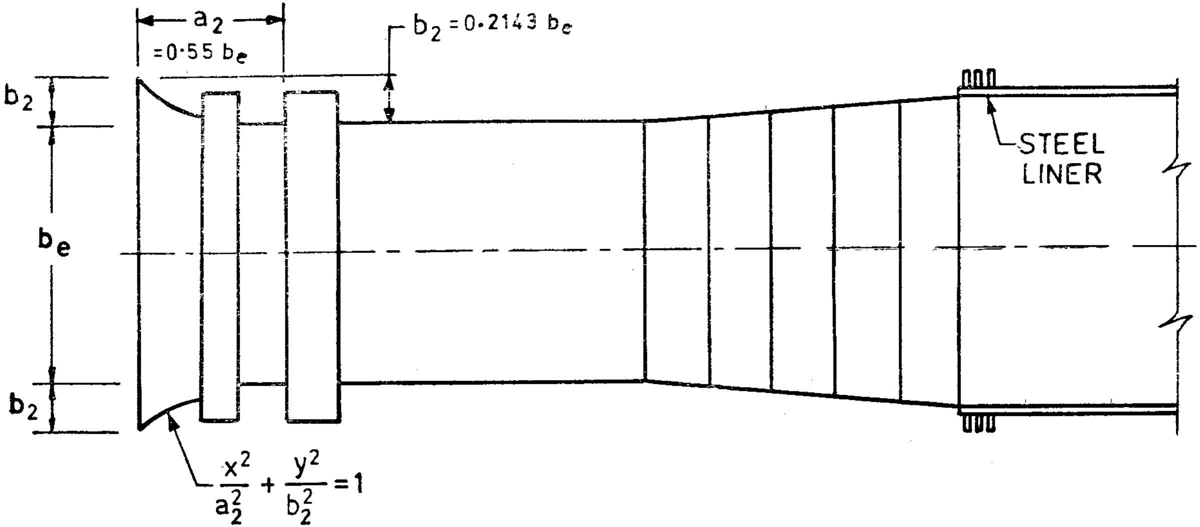

Fig. 1B Bell Mouth Details

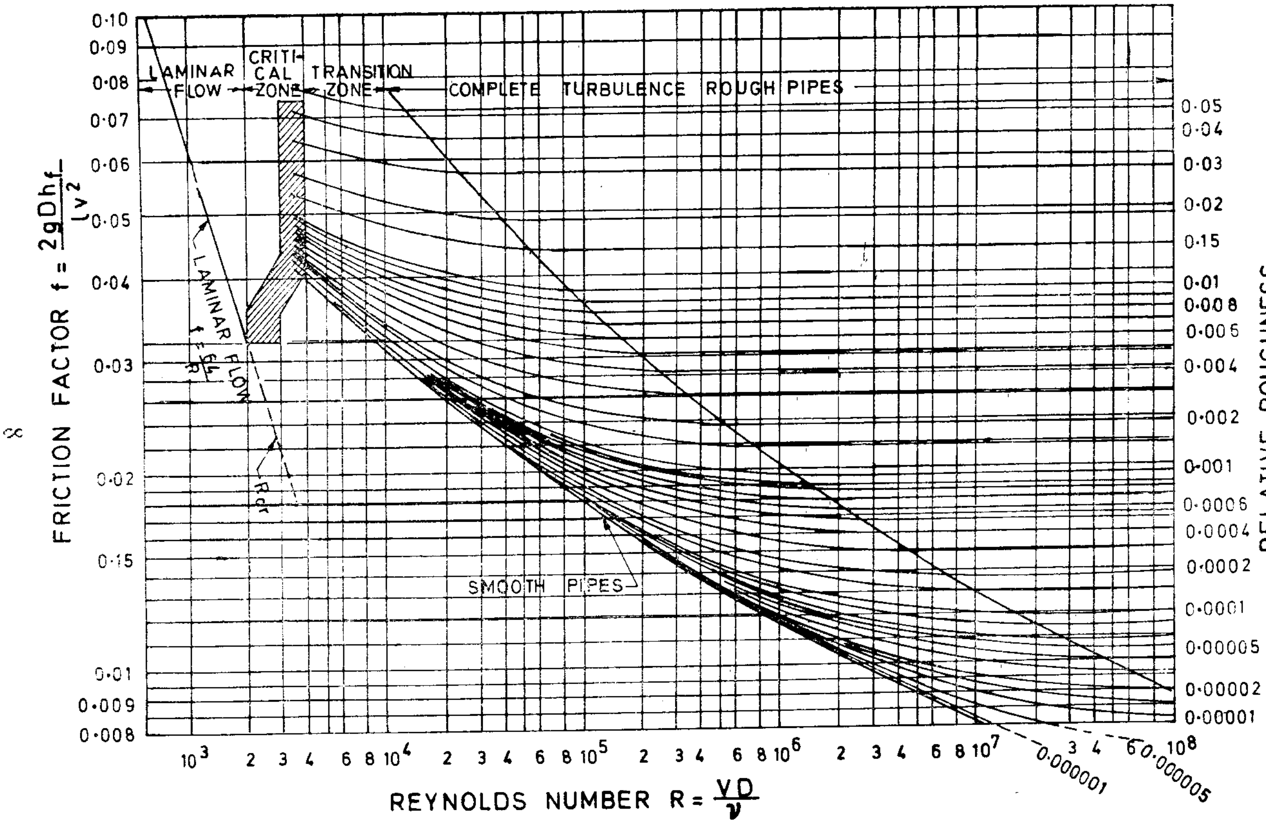

Fig. 2 Moody Diagram for Friction in Pipes

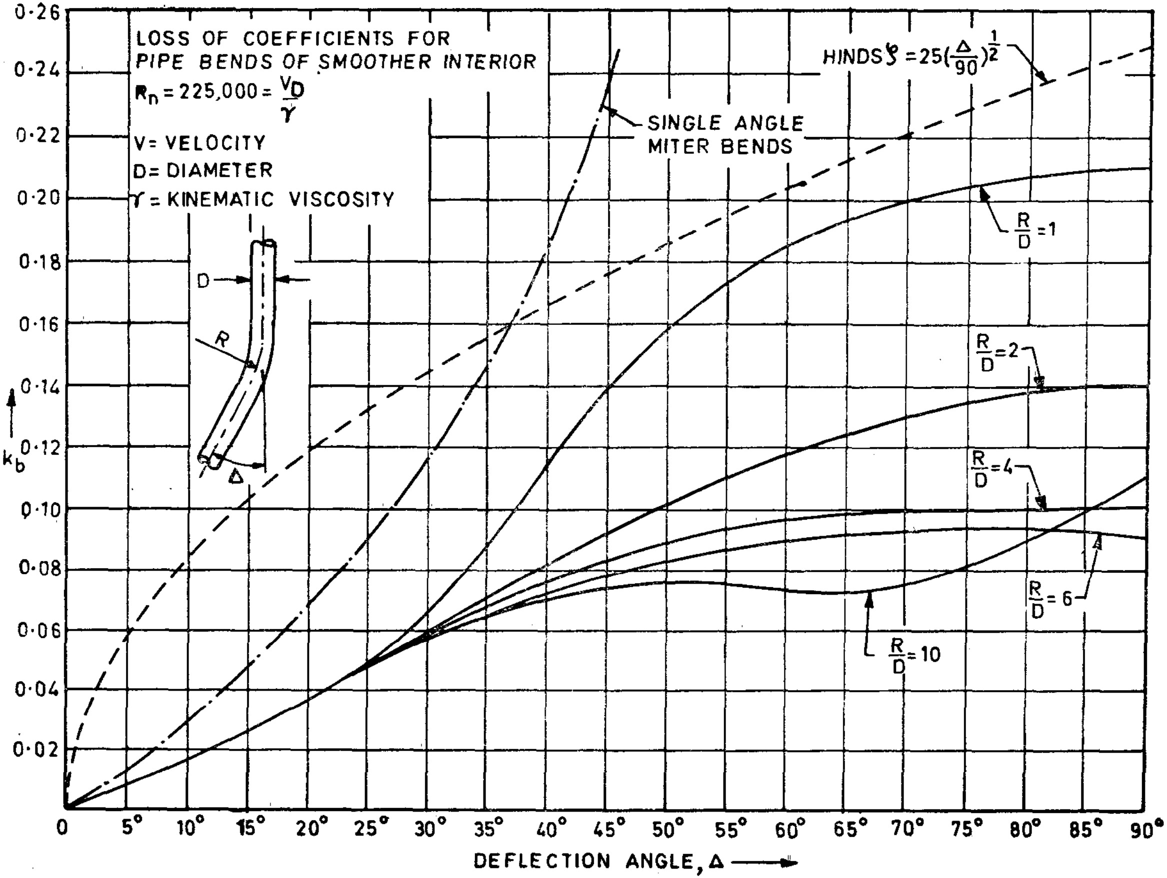

Fig. 3 Loss Coefficients for Pipe Bends of Smooth Interior

4.5.3.2 Head loss in reducer piece h_r may be estimated by the following formula:

$$h_r = k_r \left(\frac{V_2^2 - V_1^2}{2g} \right)$$

where

k_r = loss coefficient for contraction,
V_1 = velocity in normal section, and
V_2 = velocity at the contraction section.

The value of k_r shall be in accordance with IS : 4880 (Part 3)-1976*.

4.5.3.3 When a diffuser follows immediately after a bend without a straight length in-between, the loss in the diffuser will be more than that given in **4.5.3.2**. It is recommended to provide a straight length equal to the diameter of the pipe between the bend and the diffuser.

4.5.4 *Losses in Valve Passages*

4.5.4.1 Valves are usually installed at two places in the penstocks of a hydro power station — one at the upstream end and the other at the downstream end immediately ahead of the turbine. The former called as control or penstock valve is usually a butterfly valve and the latter known as inlet valve is either butterfly valve or a spherical valve. These valves remain either in fully closed or open position. Under fully opened position the losses through spherical valves are negligible. The value of loss coefficient for butterfly valve may be obtained from Fig. 4.

4.5.5 *Losses in Penstock Branches and Wyes*

4.5.5.1 A penstock bifurcation into two is termed as a wye and when more than two, it is termed as manifold.

4.5.5.2 The hydraulic losses at wyes are governed by angle of bifurcation, ratio of cross-sectional area, type and shape of bifurcation.

4.5.5.3 Various types of wyes and branches generally adopted are:

a) Wyes/branches with sharp transition,
b) Wyes/branches with conical transition, and
c) Wyes/branches with rounded corners.

---

*Code of practice for design of tunnels conveying water: Part 3 Hydraulic design (*first revision*).

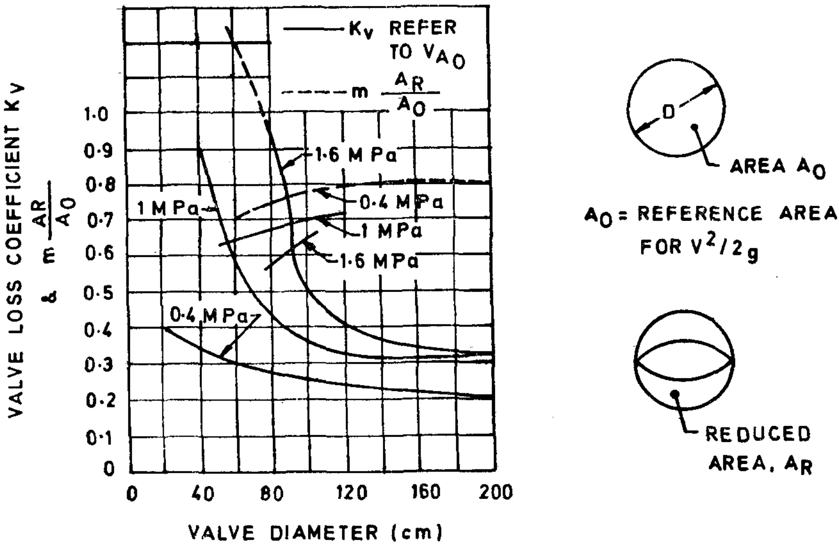

FIG. 4 GENERAL TREND OF VALVE LOSS COEFFICIENT AND RESTRICTION OF PASSAGE FOR BUTTERFLY VALVES

4.5.5.4 Figure 5 gives the head loss-coefficient for branches with sharp, rounded and conical transitions.

5. PRESSURE RISE AND PRESSURE DROP

5.1 The criteria to be adopted for the calculation of pressure rise and pressure drop, and method of computations are covered in the Indian Standard Code of practice for design of water hammer in water conductor systems (*under preparation*).

6. ECONOMIC DIAMETER OF PENSTOCK

6.1 The economic diameter of penstock is the diameter for which the annual cost, which includes the cost of power lost due to friction and charges for amortization of construction cost, maintenance, operation, etc, is the minimum.

6.2 The economic diameter is calculated by evaluating annual power loss and annual cost for maintenance and equating first derivative with respect

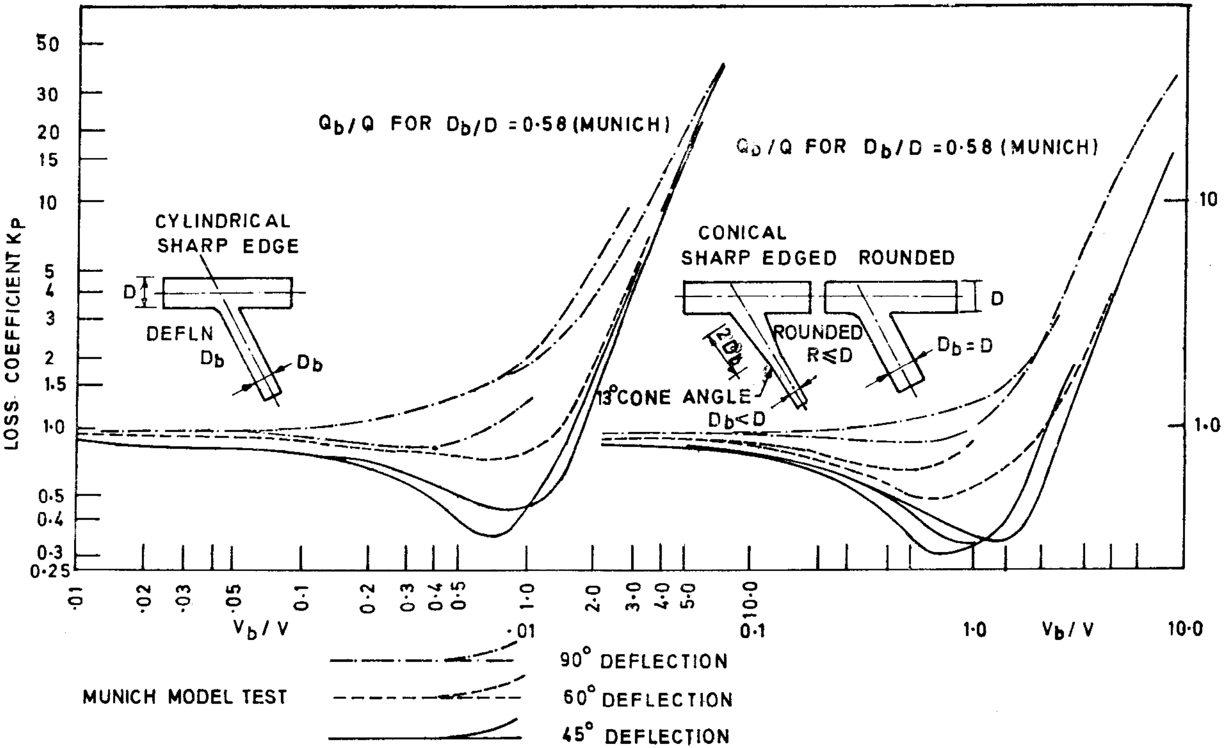

Fig. 5 Loss at Pipe Junctions with Dividing Flow

to D to zero and is given by the following equation based on Manning's formula. The derivation of the formula is given at Appendix A.

$$D^{22/3} = \frac{2{\cdot}36 \times 10^6 \times Q^3 \times n^2 \times ep_f \times C_p}{\left[1{\cdot}39\, C_e + 0{\cdot}6\, C_c + \dfrac{121\, HC_s\,(1+i)}{\sigma a\, e_j} \right] \times p}$$

where

C_c = unit cost of concrete lining in Rupees/m³;

C_e = unit cost of excavation in Rupees/m³;

C_p = cost of 1 kWh of energy in Rupees;

C_s = cost of steel in Rupees/kg;

D = diameter of the penstock;

e = overall efficiency of plant;

e_j = joint efficiency of penstock;

H = head on penstock including water hammer in m;

i = percentage by which steel in penstock is overweight due to provision of stiffeners, corrosion allowance, etc;

n = Rugosity coefficient in Manning's formula;

p = ratio of annual fixed operation and maintenance charges to construction cost of penstock;

p_f = annual load factor; and

Q = discharge through penstock in m³/s.

APPENDIX A

(*Clause* 6.2)

DERIVATION OF THE FORMULA FOR CALCULATING THE ECONOMIC DIAMETER OF PENSTOCKS

A-1. COST OF POWER LOST

A-1.1 Head Loss in Penstock/Metre Length — Head loss due to friction is given by Manning's formula:

$$h_f = \frac{v^2 n^2}{R^{4/3}} = \frac{10{\cdot}29\, Q^2 n^2}{D^{16/3}}$$

Annual cost of power lost (E_f) = $9{\cdot}804 \times Q \times h_f \times ep_f \times 8\,760 c_p$

$$E_f = \frac{0{\cdot}88 \times 10^6\, Q^3 n^2 e\, p_f\, c_p}{D^{16/3}}$$

A-2. ANNUAL CHARGES ON CAPITAL COST

A-2.1 Cost of Excavation — The cost due to excavation for laying the penstock is calculated considering the tunnel diameter to be 0·33 D in excess of penstock diameter total cost/unit length of penstock is given by:

$$\frac{\pi}{4}(D + 0{\cdot}33\,D)^2 \times C_e$$
$$= 1{\cdot}39\,D^2\,C_e$$

NOTE — 0·33 D to be varied between 0·2 D to 0·33 D depending on the diameter of penstock such that the excavated diameter is not greater than the penstock diameter by about 90 cm.

A-2.2 Cost of Concrete Lining — Cost of concrete lining in penstock has been calculated taking thickness of lining as 0·165 D. Thus cost of concrete lining is given by:

$$\pi\,(D + 0{\cdot}165\,D) \times 0{\cdot}165\,D \times C_c$$
$$= 0{\cdot}6\,D^2\,C_c$$

NOTE — 0·165 D to be varied between 0·1 D to 0·165 D, depending on the diameter of penstock such that concrete lining thickness is not greater than 30 cm.

A-2.3 Cost of Steel in Penstock

$$\text{Steel lining thickness}\quad t = \frac{pd}{2\sigma_a\,e_j} = \frac{0{\cdot}1\,HD}{2\,\sigma_a\,e_j}$$

$$\text{Penstock cost} = \frac{\pi\,Dt\,(1+2)\,7\,850 \times C_s}{2\,\sigma_a \times 9{\cdot}81 \times e_j}$$

$$= \frac{120{\cdot}93\,HD^2 \times C_s\,(1+i)}{\sigma_a \times e_j}$$

A-2.4 Annual Charges on Capital Cost — The annual cost of penstock is expressed by:

$$E_p = \frac{[D^2\,(1{\cdot}39\,C_e + 0{\cdot}6\,C_c + 120{\cdot}93\,HC_s\,(1+i)] \times p}{\sigma_a\,e_j}$$

A-3. ECONOMIC DIAMETER

A-3.1 Total Annual Cost (E) $= E_p + E_f$

Economical diameter is obtained by:

$$\frac{\delta\,(E_p + E_f)}{\delta\,D} = 0.$$

$$D^{22/3} = \frac{2{\cdot}36 \times 10^6 \times Q^3 \times n^2 \times ep_f \times C_s}{\left[1{\cdot}39\,C_e + 0{\cdot}6\,C_c + \dfrac{121\,HCs\,(1+i)}{\sigma_a \times e_j}\right] \times p}$$

(*Continued from page* 2)

Members	*Representing*
SHRI N. C. JAIN	Irrigation Department, Government of Uttar Pradesh, Lucknow
DR ZAFAR MEHDI	Bharat Heavy Electricals Ltd, Bhopal
SHRI J. L. KHOSA (*Alternate*)	
SHRI C. GANESA PILLAI	Kerala State Electricity Board, Trivandrum
SHRI A. R. RAGHAVAN	Tamilnadu Electricity Board, Madras
SHRI T. RAMASWAMY	Indian Hume Pipe Co Ltd, Bombay
SHRI B. RAMASWAMY (*Alternate*)	
DR H. R. SHARMA	Central Electricity Authority, New Delhi
SHRI B. THOMAS	Central Water & Power Research Station, Pune
SHRI R. VIJAYAN	In personal capacity [*35/136 (2) Kamaldoth Lane, Cochin*]
SHRI N. G. KURUP (*Alternate*)	

INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

Base Units

Quantity	*Unit*	*Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

Supplementary Units

Quantity	*Unit*	*Symbol*
Plane angle	radian	rad
Solid angle	steradian	sr

Derived Units

Quantity	*Unit*	*Symbol*	*Definition*
Force	newton	N	1 N = 1 kg.m/s^2
Energy	joule	J	1 J = 1 N.m
Power	watt	W	1 W = 1 J/s
Flux	weber	Wb	1 Wb = 1 V.s
Flux density	tesla	T	1 T = 1 Wb/m^2
Frequency	hertz	Hz	1 Hz = 1 c/s (s^{-1})
Electric conductance	siemens	S	1 S = 1 A/V
Electromotive force	volt	V	1 V = 1 W/A
Pressure, stress	pascal	Pa	1 Pa = 1 N/m^2