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## भाग 2 शैल में निमज्जित/अंतः स्थापित पात नल

*Indian Standard*

# STRUCTURAL DESIGN OF PENSTOCKS — CRITERIA

## PART 2 BURIED/EMBEDDED PENSTOCKS IN ROCK

UDC 627·844



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

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Price Group 4

Water Conductor Systems Sectional Committee, RVD 14

## FOREWORD

This Indian Standard ( Part 2 ) was adopted by the Bureau of Indian Standards, after the draft finalized by the Water Conductor Systems Sectional Committee had been approved by the River Valley Division Council.

Penstocks carry water from surge tanks or directly from a reservoir to the power house. Such penstocks may be laid on the surface or buried/embedded in rock or concrete. Part 1 of this standard covers the criteria for structural details of surface penstocks and this part covers the criteria for structural design of buried/embedded penstocks in rock or concrete.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values ( *revised* )'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

*Indian Standard*

# STRUCTURAL DESIGN OF PENSTOCKS — CRITERIA

## PART 2 BURIED/EMBEDDED PENSTOCKS IN ROCK

## 1 SCOPE

**1.1** This standard ( Part 2 ) lays down the general requirements and design of circular penstocks, buried/embedded in rock or concrete, for conveyance of water from a reservoir, pond or surge tank to a hydraulic turbine in hydro-power plants.

**1.2** This standard does not cover the design of specials like manifolds, wye-pieces, transitions, anchor blocks, etc.

## 2 REFERENCES

The Indian Standards listed in Annex A are necessary adjuncts to this standard.

## 3 HYDRAULIC DESIGN

For hydraulic design of penstocks reference may be made to IS 11625 : 1986.

## 4 MATERIAL AND ALLOWABLE STRESSES

### 4.1 Material

**4.1.1** Steel to be used for the fabrication of penstocks of a hydro-electric project should meet the following requirements:

a) It should stand against maximum internal pressure including dynamic pressure,

b) It should stand against frequent dynamic changes,

c) It should have required impact strength to be able to deform plastically in the presence of stress concentrations at notches and bends,

d) It should have good weldability without preheating, and

e) It should not require any stress relieving after welding.

The requirements (a) to (c) are essential while requirements (d) and (e) are preferable.

**4.1.2** The steel plates to be used for fabrication of penstock liners should be of fire box quality conforming to IS 2002 : 1992, IS 2041 : 1982 or IS 8500 : 1992.

**4.1.3** Nothing in the foregoing should preclude the use of material where so agreed by the purchaser. It is recommended that, in such cases, particular attention be given to the weldability and ductility of the material proposed to be used. No such material should have elongation ( in percent ) on a gauge length of $5.65\sqrt{S_0}$, less than ( $100-R_m$ ) / 2·2 where $S_0$ is the original area of cross-section and $R_m$ is the actual tensile strength in N/mm$^2$ at room temperature, subject to a minimum of 16 percent for carbon and carbon manganese steels, 14 percent for alloy steels other than austenitic steels and 25 percent for austenitic steels for test pieces obtained, prepared and tested in accordance with appropriate Indian Standard.

**4.1.4** Materials used for supporting lugs, stiffeners and other similar non-pressure parts welded to penstocks should be of weldable quality and suitable in other respects for intended service.

### 4.2 Allowable Stresses

**4.2.1** The allowable stresses and the factor of safety to be adopted depend upon the yield point stress and ultimate tensile strength of the steel, loading condition and the location where steel lining is provided.

**4.2.2** Following allowable stresses should be adopted in design of steel penstocks:

a) In normal operating condition, the design stresses should not exceed one-third of the minimum ultimate tensile strength or 60 percent of minimum yield point stress of steel, whichever is less.

b) In intermittent condition, the design stresses should not exceed 40 percent of the minimum ultimate tensile strength or two-thirds of minimum yield point stress of steel, whichever is less.

c) In the emergency condition, the design stress should not exceed two-thirds of minimum ultimate tensile strength or 90 percent of minimum yield point stress of steel, whichever is less, and

d) In exceptional condition, the design stress should not exceed the minimum yield point stress.

**4.2.3** When rock participation is considered in the design, the stresses in steel lining under normal loading condition without rock participation should also be checked and should not exceed 90 percent of minimum yield point stress or two-thirds of minimum ultimate tensile strength, whichever is less. In intermittent and emergency conditions of loading it should not exceed the minimum yield point stress.

**4.2.4** Loading conditions should be considered as given below:

a) Normal condition includes static head along with pressure rise due to normal operation or head at transient maximum surge, whichever is higher.

b) Intermittent condition includes those during filling and draining of penstocks and maximum surge in combination with pressure rise during normal operation.

c) Emergency condition includes partial gate closure in critical time of penstock ( 2L/a seconds ) at maximum rate, and the cushioning stroke being inoperative in one unit.

d) Exceptional condition includes slam shut, malfunctioning of control equipment in the most adverse manner resulting in odd situation of extreme loading. This should not be taken as a design criteria.

**4.3 Joint Efficiency**

**4.3.1** Joint efficiency or weld factor assumed for purpose of design varies for different kind of joints and different methods of inspection and testing. The joint efficiency also varies for different type of steel.

**4.3.2** Joint efficiency as specified in Table 1.1 of IS 2825 : 1969 should be adopted.

**4.4** For liner thickness exceeding 38 mm and specials like manifolds, transitions, etc, stress relieving should be done as specified in IS 2825 : 1969.

## 5 DESIGN LOADS

The steel lining has to withstand the internal water pressure as well as external pressures which may be caused either during grouting operations or when the penstock is dewatered.

**5.1 Internal Pressure**

**5.1.1** The steel lining of a penstock is designed for maximum internal pressure which is caused due to maximum water level in reservoir or in surge tank, as the case may be, plus the anticipated increase in pressure due to water hammer effect development when arresting or releasing the flow of water. It should be computed for both normal as well as emergency conditions. The plate thickness of the penstock should be checked for both these conditions.

**5.1.2** *Water Hammer Effect*

Rapid opening or closing of the turbine gates produces a pressure wave in the penstock, termed as water hammer effect. Detailed water hammer analysis for various conditions of operations as specified in IS 12967 ( Part 1 ) : 1990 should be carried out for computing water hammer effect.

**5.1.3** *Pressure Wave Velocity*

i) The pressure wave velocity in a steel penstock carrying water may be computed as follows:

$$a = \frac{1\,425}{1 + ( d/100t )}$$

where

$a$ = pressure wave velocity in m/s,

$d$ = diameter of penstock in m, and

$t$ = thickness of penstock shell in m.

ii) For a pipe concreted in solid rock, the pressure wave velocity may be taken equal to 1 425 m/s ( velocity of sound in water )

**5.1.4** *Pressure Rise Gradient*

Pressure rise due to water hammer is measured above static water level in reservoir or maximum upsurge level in case of surge tank and it is assumed to vary uniformly along penstock, from maximum at turbine end to zero at reservoir level or maximum upsurge level, as the case may be, as given in IS 7396 ( Part 1 ) : 1985.

**5.2 External Pressure**

**5.2.1** The steel lining should be designed for the external water pressure head which is either the difference between the ground level vertically above the penstock and the penstock invert level or the maximum level from which the water is likely to find its way around steel lining, whichever is less.

**5.2.2** The liner should also be checked against grouting pressure during construction.

**5.3 Longitudinal Stresses Caused by Radial Strain**

Radial expansion of steel caused by internal pressure tends to cause longitudinal contraction with corresponding tensile stress equal to 0·303 times the hoop tension in the circular lining.

## 6 STRUCTURAL DESIGN OF STEEL LINING

### 6.1 Design for Internal Pressure

The stresses in the steel liner and the surrounding concrete/rock may be computed using the formulae given in **6.1.1** to **6.1.3**.

**6.1.1** *Hoop Stress in Penstock Without Rock Participation*

If the surrounding rock is very badly fractured and weak or the minimum rock cover is inadequate, the steel lining should be designed for full internal pressure. The hoop stress in such case may be computed using the formula:

$$f_{st} = \frac{P.R}{t}$$

where

$f_{st}$ = hoop tensile stress in steel liner in N/m², 
$P$ = internal pressure in N/m², 
$R$ = internal radius of penstock in m, and 
$t$ = thickness of liner shell in m.

NOTE — Rock cover is considered inadequate when it is less than 40 percent vertically and 120 percent horizontally of the internal pressure head under normal loading condition.

**6.1.2** *Hoop Stress in Penstock in Unfissured Concrete*

If the penstock is embedded in well reinforced, homogeneous mass concrete without fissures or cracks, for example, penstock through a concrete gravity dam adequately reinforced against cracking, the hoop stress in the steel liner and the surrounding concrete may be computed using the following formulae:

$$P_s = P \left[ \frac{1}{1 + \frac{E_c R}{E_s t} \cdot \frac{1 - \mu_s^2}{(K_1 + \mu_c)}} \right] \quad \text{... (i)}$$

$$K_1 = \frac{C^2 + R^2}{C^2 - R^2} \quad \text{...... (ii)}$$

$$f_{st} = \frac{P_s . R}{t} \quad \text{...... (iii)}$$

$$f_{ct} = (P - P_s) \times \frac{(C^2 + R^2)}{(C^2 - R^2)} \quad \text{... (iv)}$$

where

$P_s$ = pressure shared by steel liner in N/m², 
$P$ = total internal pressure in N/m², 
$R$ = internal radius of penstock in m, 
$C$ = radius of external surface of concrete in m, 
$t$ = thickness of steel lining in m, 
$E_s$ = modulus of elasticity of concrete in N/m². 
$E_s$ = modulus of elasticity of steel in N/m², 
$\mu_s$ = Poisson's ratio for steel, 
$\mu_c$ = Poisson's ratio for concrete, 
$f_{st}$ = hoop tensile stress in steel liner in N/m², and 
$f_{ct}$ = hoop tensile stress in concrete at inner surface of concrete in N/m².

**6.1.3** If the penstock is embedded in fissured concrete and rock, the stress in steel and rock may be computed using the following formulae:

$$P_o = \frac{Y_{ot}}{R^2} \times \frac{E_s}{1 - \mu_s^2} \quad \text{.................. (v)}$$

$$M = 1 + \frac{1}{2(1 + \mu_r)} \left[ \frac{E_r}{E_c} \left( \frac{C^2 - R^2}{RC} \right) + \frac{d^2 - C^2}{Cd} \right] \quad \text{.................. (vi)}$$

$$P_s = P_o + (P - P_o) \left[ \frac{1}{1 + \frac{E_r R}{E_s t M} \left[ \frac{1 - \mu_s^2}{1 + \mu_r} \right]} \right] \quad \text{......... (vii)}$$

$$f_{st} = \frac{P_s R}{t} \quad \text{.................. (viii)}$$

$$f_{rt} = \frac{(P - P_s) R}{d} \quad \text{.................. (ix)}$$

where

$M$ = a dimensionless parameter, 
$f_{st}$ = hoop tensile stress in liner in N/m², 
$P$ = total internal pressure in N/m², 
$P_s$ = pressure shared by steel lining in N/m², 
$P_o$ = pressure required to close the gap $Y_o$ between liner and concrete/rock, 
$Y_o$ = initial gap between the liner and the concrete caused due to shrinkage and creep of concrete and temperature effect in m, 
$R$ = internal radius of penstock in m, 
$C$ = outside radius of concrete lining in m, 
$d$ = radius to the end of radial fissure in rock in m ( where the *in-situ* compressive stresses in rock are just exceeded by the tensile stresses caused by internal pressure ), 
$t$ = thickness of steel liner in m, 
$E_s$ = modulus of elasticity for steel in N/m²,

$E_r$ = modulus of elasticity for rockmass in $N/m^2$,

$E_c$ = modulus of elasticity for concrete in $N/m^2$,

$\mu_s$ = Poisson's ratio for steel,

$\mu_r$ = Poisson's ratio for rockmass, and

$f_{rt}$ = tangential tensile stress in rockmass due to internal pressure at d metres away from centre of penstock.

**6.1.4** The maximum hoop tensile stress in steel liner $f_{st}$ should not exceed the product of joint efficiency and the allowable stress.

## 6.2 Design for External Pressure

**6.2.1** *Critical External Pressure for Unstiffened Shell*

Critical external pressure for unstiffened penstock liner shell may be computed using the following formulae:

A) Vaughan's formula

$$\frac{13K^2}{4E'} P^2_{cr} + 2P_{cr} \left( 1 + 3K\frac{Y_0}{R} - \frac{F_y K}{2E'} \right) - \left( \frac{4F_y}{K} - \frac{F^2_y}{E'} \right) = 0$$

where

$K$ = ratio of pipe diameter to plate thickness,

$E' = \frac{E_s}{1 - \mu^2_s}$,

$E_s$ = modulus of elasticity of steel in $N/m^2$,

$\mu_s$ = Poisson's ratio of steel,

$P_{cr}$ = critical external pressure at buckling in $N/m^2$,

$Y_0$ = initial gap between steel lining and concrete in m,

$R$ = radius of steel liner in m, and

$F_y$ = yield point stress in steel in $N/m^2$.

B) Amstutz's formula

The critical stresses in the liner are given by solution of the following two equations:

$$\left( \frac{f_n}{E'} + \frac{Y_0}{R} \right) \left[ 1 + \frac{3K^2 . f_n}{E'} \right]^{3/2} = 1.68K \frac{f'_y - f_n}{E'} \times \left[ 1 - \frac{K}{4} \times \frac{f'_y - f_n}{E'} \right]$$

and

$$1 - \frac{P_{cr} . K}{2f_n} = 0.175 \frac{K}{E'} ( f'_y - f_n )$$

where

$$K = \frac{2R}{t}$$

$$E' = \frac{E_s}{1 - \mu^2_s}$$

$$f'_y = \frac{f_y}{\sqrt{1 - \mu_s + \mu^2_s}}$$

$f_y$ = yield stress of steel in $N/m^2$,

$E_s$ = modulus of elasticity of steel in $N/m^2$,

$\mu_s$ = Poisson's ratio of steel,

$R$ = radius of penstock in m,

$Y_0$ = initial gap between liner and concrete in m,

$f_n$ = allowable stress in steel in $N/m^2$,

$P_{cr}$ = critical external pressure in $N/m^2$, and

$t$ = thickness of steel liner in m.

NOTE — Lower of the two values of critical external pressure calculated by above formulae should be adopted.

**6.2.2** The maximum external pressure on the penstock should not exceed two-thirds times the critical external pressure calculated according to **6.2.1.** If the maximum external pressure exceeds the value equal to two-thirds times the critical external pressure for unstiffened shell, stiffeners should be provided to prevent buckling.

**6.2.3** *Critical External Pressure for Stiffened Shell*

**6.2.3.1** Critical external pressure for steel liner with stiffening rings should be computed by Timoshenko equation. The critical external pressure should not be less than 1.5 times the maximum external pressure.

Timoshenko equation:

$$P_{cr} = \frac{2E'}{K} \left[ \frac{1 - \mu^2_s}{( n^2 - 1 ) \left( 1 + \frac{4n^2\lambda^2}{\pi^2 K^2} \right)^2} + \frac{1}{3K^2} \left\{ ( n^2 - 1 ) + \frac{2n^2 - 1 - \mu_s}{\frac{4n^2\lambda^2}{\pi^2 K^2} - 1} \right\} \right]$$

where

$$K = \frac{2R}{t}$$

$$\lambda = \frac{L}{t}$$

$$E' = \frac{E_s}{1 - \mu^2_s}$$

$t$ = thickness of liner plate in m.

$R$ = radius of penstock in m.

$L$ = spacing of stiffener rings in m.

$n$ = number of full waves on buckling chosen to make $P_{cr}$ a minimum. For n values varying from 1 to 18, the values of $P_{cr}$ should be calculated and a graph plotted to obtain minimum $P_{cr}$.

$P_{cr}$ = critical external pressure in kN/m².

$E_s$ = modulus of elasticity for steel in kN/m².

$\mu_s$ = Poisson's ratio of steel.

**6.2.3.2** Critical external pressure may also be determined directly from Fig. 1 based on the formula given in **6.2.3.1**.

**6.2.4** *Spacing of Stiffener Ring*

The centre to centre spacing of stiffener rings should not be more than 240 times and not less than 60 times the thickness of steel liner.

**6.2.5** *Size of Stiffener Rings*

The size of stiffener rings may be worked out using Vaughan's formulae by trial and error method so that the external critical pressure is not less than 1·5 times the maximum external pressure.

$$K_1 P^3_{cr} + K_2 P^2_{cr} - K_3 P_{cr} + K_4 = 0$$

where

$$K_1 = \frac{R^4}{E' t'}$$

$$K_2 = R^3 \left( \frac{y_0}{R} + \frac{I}{R.A.V} \right)$$

$$K_3 = \frac{I. \sigma_y. t'}{A. V.} \left( \frac{I}{A.V} + R \right)$$

$$K_4 = \frac{I^2 \sigma_y^2 t^2}{4A^2 V^2 R}$$

$R$ = radius of penstock in m,

$A$ = total area of the composite section in m²,

$A_r$ = sectional area of the stiffener ring in m²,

$t'$ = equivalent thickness in m,

$= t + \frac{A_r}{l}$

$l$ = associated width in m,

$= b + 1{\cdot}56\sqrt{R.\,t}$

$b$ = contact zone width of stiffener on ferrule in m,

$I$ = moment of inertia of the combined section about neutral axis in m⁴,

$V$ = distance between the neutral axis of the combined section and the outer extreme edge of the stiffener in m,

$P_{cr}$ = external critical pressure in N/m²,

$t$ = thickness of liner in m,

$\sigma_y$ = permissible yield stress of liner in N/m², and

$Y_0$ = initial freedom of the shell to become distorted which is algebraic sum of initial out of roundness, thermal shrinkage or expansion after installation but before loading expansion due to shrinkage, due to prestress, etc, in m.

## 7 THICKNESS OF LINING

**7.1** The minimum thickness of the lining should not be less than:

a) minimum handling thickness,

b) thickness required for internal pressure or external pressure ( $t$ ) plus 1·5 mm corrosion allowance. If the inside surface of the penstock is painted with some anticorrosive paint like epoxy paint, corrosion allowance may be neglected.

**7.2** Regardless of pressure conditions, a minimum handling thickness given by following formula is recommended to provide rigidity required during fabrication:

$$t_0 = \frac{R + 0{\cdot}25}{200}$$

where

$t_0$ = minimum handling thickness in m, and

$R$ = radius of penstock in m.

## 8 CHANGE IN THE THICKNESS OF STEEL LINING

**8.1** The thickness of steel lining at different locations depends upon various factors. When the penstock passes through different layers of rock, the steel thickness provided in bad or medium layer of rock is extended into next better layer for a length equal to at least one diameter of the penstock.

**8.2** The difference in steel plate thicknesses in adjoining ferrules should not be more than 5 mm.

**8.3** When lining emerges out of a tunnel, it should be designed for full internal pressure and due care should be taken of stress concentrations occurring in the surrounding rock.

## 9 CONCRETE LINING AROUND THE LINER

The concrete lining around the penstock liner and the rock supports, if required, should be designed according to provisions of IS 4880 ( Part 4 ) : 1971 and IS 4880 ( Part 5 ) : 1972.

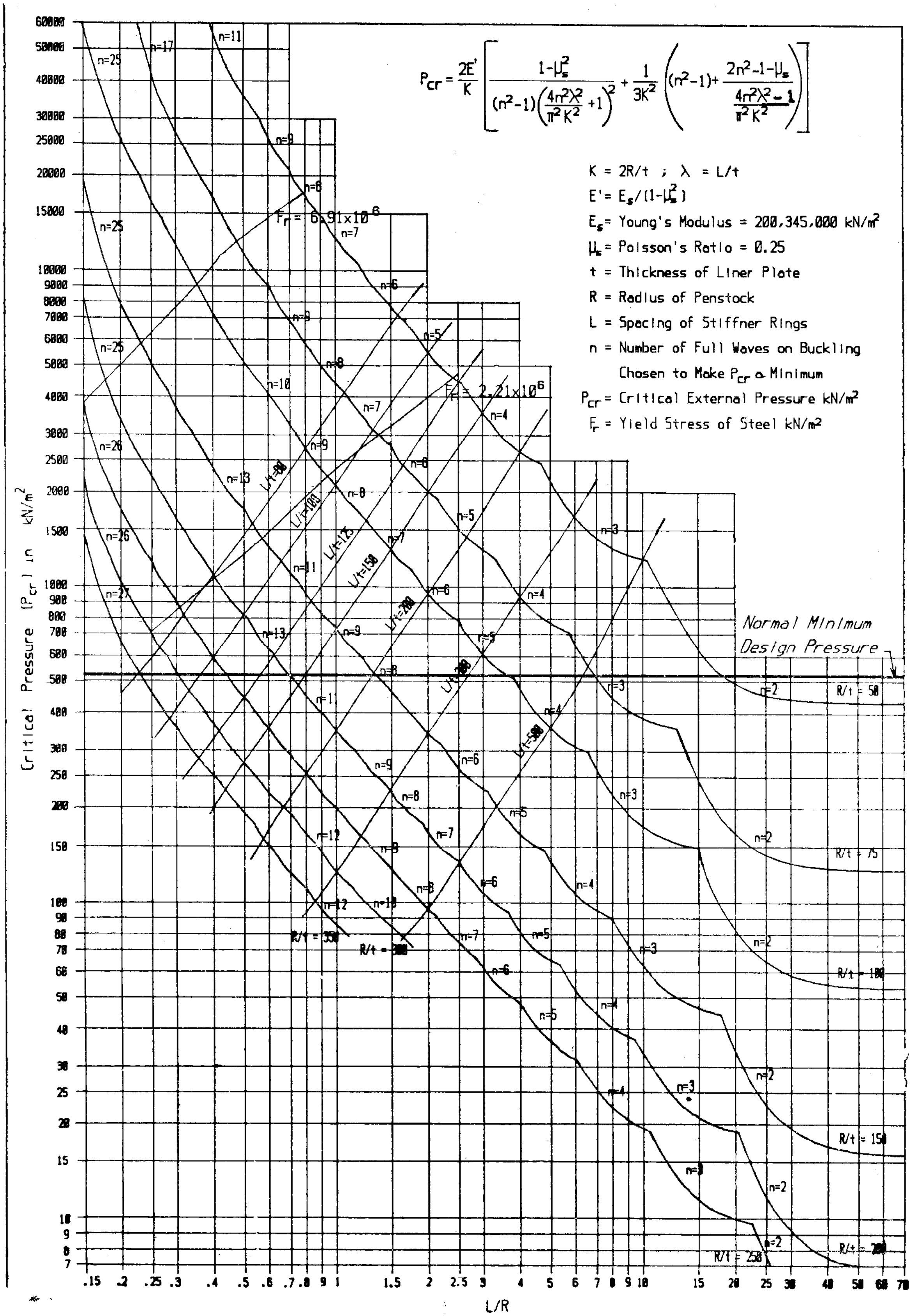


FIG. 1 DIAGRAM FOR CRITICAL EXTERNAL PRESSURE

# ANNEX A

( *Clause* 2 )

## LIST OF REFERRED INDIAN STANDARDS

| *IS No.* | *Title* |
|---|---|
| 2002 : 1992 | Steel plates for pressure vessels for intermediate and high temperature service including boilers ( *second revision* ) |
| 2041 : 1982 | Steel plate for pressure vessels used at moderate and low temperature ( *first revision* ) |
| 2825 : 1969 | Code for unfired pressure vessels |
| 4880 ( Part 4 ) : 1971 | Code of practice for design of tunnels conveying water : Part 4 Structural design of concrete lining in rock |
| 4880 ( Part 5 ) : 1972 | Code of practice for design of tunnels conveying water : Part 5 Structural design of concrete lining in soft strata and soils |
| 7396 ( Part 1 ) : 1985 | Criteria for hydraulic design of surge tanks : Part 1 Simple, restricted orifice and differential surge tanks ( *first revision* ) |
| 8500 : 1992 | Structural steel — Microalloyed ( medium and high strength qualities ) ( *first revision* ) |
| 11625 : 1986 | Criteria for hydraulic design of penstocks |
| 12967 ( Part 1 ) : 1990 | Code of practice for analysis ofhy draulic transients in hydro-electric and pumping plants : Part 1 Criteria for analysis |

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Amendments are issued to standards as the need arises on the basis of comments. Standards are also reviewed periodically; a standard along with amendments is reaffirmed when such review indicates that no changes are needed; if the review indicates that changes are needed, it is taken up for revision. Users of Indian Standards should ascertain that they are in possession of the latest amendments or editon by referring to the latest issue of 'BIS Handbook' and 'Standards Monthly Addition'.

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**Amendments Issued Since Publication**

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|---|---|---|
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BUREAU OF INDIAN STANDARDS

**Headquarters:**
Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi 110002
Telephones : 331 01 31, 331 13 75

Telegrams : Manaksanstha
( Common to all Offices )

| Regional Offices : | Telephone |
|---|---|
| Central : Manak Bhavan, 9 Bahadur Shah Zafar Marg NEW DELHI 110002 | 331 01 31<br>331 13 75 |
| Eastern : 1/14 C. I. T. Scheme VIII M, V. I. P. Road, Maniktola CALCUTTA 700054 | 37 84 99, 37 85 61<br>37 86 26, 37 86 62 |
| Northern : SCO 335-336, Sector 34-A, CHANDIGARH 160022 | 60 38 43,<br>60 20 25, |
| Southern : C. I. T. Campus, IV Cross Road, MADRAS 600113 | 235 02 16, 235 04 42<br>235 15 19, 235 23 15 |
| Western : Manakalaya, E9 MIDC, Marol, Andheri ( East ) BOMBAY 400093 | 632 92 95, 632 78 58<br>632 78 91, 632 78 92 |

Branch : AHMADABAD. BANGALORE. BHOPAL. BHUBANESHWAR. COIMBATORE. FARIDABAD. GHAZIABAD, GUWAHATI. HYDERABAD. JAIPUR. KANPUR LUCKNOW. PATNA. THIRUVANANTHPURAM.

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