*Draft for Comment Only*

**Doc. WRD 14(546)**
*December 2011*

**BUREAU OF INDIAN STANDARDS**

*Draft Indian Standard*

# CODE OF PRACTICE FOR DESIGN OF TUNNELS CONVEYING WATER
# PART VII STRUCTURAL DESIGN OF STEEL LINING

*[First Revision of IS 4880 (Part VII)]*



Last date for receipt of comments is 25 Feb 2012

FOREWORD
(Formal clauses will be added later)

The type of lining chosen for tunnels depends upon the rock properties and rock cover over the tunnel and the type of tunnel itself. There is, so far, no generally accepted method for the design of steel lining. The purpose of this code is to outline the criteria to be adopted in the design. Steel lining is a steel plate provided to inner surface of water carrying tunnel for any or all of the following purposes:

a) To resist bursting pressure of water carried by the tunnel;
b) To prevent water losses or seepage into the surrounding rock; and
c) To provide a smooth surface for flow of water so as to minimize the head loss.

This standard has been published in seven parts. Other parts of this standard are as follows:

IS 4880(Part I):1987 Code of practice for design of tunnels conveying water: Part I General design

IS 4880(Part II):1987 Code of practice for design of tunnels conveying water: Part II Geometric design

IS 4880(Part III):1987 Code of practice for design of tunnels conveying water: Part III Hydraulic design

IS 4880(Part IV):1987 Code of practice for design of tunnels conveying water: Part IV Structural design of concrete lining is rock

IS 4880(Part V):1987 Code of practice for design of tunnels conveying water: Part V Structural design of concrete lining in soft strata and soils

IS 4880(Part VI):1987 Code of practice for design of tunnels conveying water: Part VI Tunnel support

This standard is one of a series of Indian Standards on tunnels. This standard was first published in 1975. This revision has been taken up as a result of the experience gained while using the standard resulting in the modifications of certain provisions relating to reducing the upper range of limiting velocity and correction in the formula to calculate rock participation. Additional clause 4.3.2.1 has been inserted to make it in line with clause 4.2.3 of IS 11639(Part 2):1995 Structural design of penstocks – Criteria: Part 2 Buried/embedded penstocks in rock.

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 same as that of the specified value in this standard.

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**CODE OF PRACTICE FOR DESIGN OF TUNNELS CONVEYING WATER**
**PART VII STRUCTURAL DESIGN OF STEEL LINING**
*[First Revision of IS 4880 (Part VII)]*

## 1. SCOPE

**1.1** This standard (Part VII) covers the general requirements and design of steel lining of tunnels for conveyance of water from reservoirs to hydraulic turbines in hydro-power plants or *vice versa* in case of reversible pump turbines in pumped storage schemes or for other similar installations.

**1.2** This code does not cover the design of specials like manifolds, wye-piece, transitions, etc.

## 2. REFERENCE

The following Indian Standards contain provisions which through reference in this text, constitute provision of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, the parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below:

IS 2002:1992 Steel plates for pressure vessels for intermediate and high temperature service including boilers (second revision)

IS 2041:1995 Steel plates for pressure vessels used at moderate and low temperature (second revision)

IS 4880(Part III):1976 Code of practice for design of tunnels conveying water: Part III Hydraulic design (first revision)

IS 9595:1996 Metal arc welding of carbon & carbon manganese steels – Recommendation (first revision)

## 3. GENERAL

### 3.1 Dimensions and Shape

**3.1.1** The circular section of the tunnel is most suitable for lining from point of view of design and fabrication. Steel liner in rectangular shape is generally not provided.

**3.1.2** The most economical dimensions and shape of the pressure conduit to be lined should be decided on the basis of the economic studies. The particular size, for which the sum of the value of power annually lost and the annual charges is at a minimum, is selected. Provisions of 2.3.1.1 of IS 4880(Part III) are applicable in this connection.

**3.2 Contraction and Expansion** – To minimize head losses and to avoid cavitation tendencies along the tunnel surface contraction and expansion transitions shall be designed in accordance with IS 4880(Part III).

**3.3 Limiting Velocity** – The velocities in a steel lined tunnel depend on the economic considerations and governing conditions of turbine. These velocities may range between 1.6 and 7 m/s. Where economic consideration is not the criteria and in exceptional cases higher velocity more than 7 m/sec may be permitted subject to suitable precautions.

NOTE – Low velocities normally occur when steel lining is provided in shorter lengths in a concrete lines tunnel where reducing the diameter may not be practicable or desirable.

**3.4 Loss of Head** – The loss of head due to different reasons shall be worked out conforming to IS 4880(Part III).

## 4. DESIGN

**4.1 Material** - The steels plates used shall conform to IS 2002 and IS 2041.

**4.2 Design Stresses and Factor of Safety** – The design stresses and factor of safety to be adopted depend upon the yield points stress of steel and location where steel lining is to be provided.

**4.2.1 –** For steel lining to be provided in tunnel where sharing of internal load by rock is not to be taken into account the design stress to be adopted shall be equal to the yield point stress with a factor of safety of 1.67.

**4.2.2 –** In case of pressure tunnels passing through rock and requiring steel lining it is a general practice to resume that the rock shares the internal water pressure to some extent depending upon its and rock cover. Wherever rock share is considered, the allowable design stress for shell shall not exceed 0.67 times yield stress of steel.

**4.2.2.1** 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.

**4.2.3** For emergency conditions expected to exist for short period of time and at infrequent intervals, design stress equal to yield point stress with factor of safety of one shall be adopted.

**4.3 Joint Efficiency** - Joint Efficiency or weld factor assumed for purpose of design varies for different kinds of joints and different methods of inspection and testing. The joint efficiency also varies for different types of steel (Refer IS 9595:1996).

**4.3.1** - For all longitudinal welded joints if completely radiographed or ultrasonically tested and weld defects repaired, the joint efficiency is taken as 100 percent otherwise the efficiency is taken as 80 percent.

## 5. DESIGN LOADS

**5.1 Internal Pressure –** The steel lining of a tunnel is designed for maximum internal pressure. The maximum internal pressure is the load on the pipe per unit area caused by the maximum static water head and the anticipated increase in the static head due to water hammer effect development when arresting or releasing the flow of water. Water hammer analysis may e done to determine the effect of water hammer on the lining of tunnel.

**5.2 External Pressure** – The steel lining shall be designed for the external water pressure which is either the difference between the ground level vertically above the tunnel and the tunnel invert level, or the maximum level from which water is likely to find its way around the steel lining. 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 of hoop tension in circular lining. However, this is generally negligible.

## 6. THICKNESS OF LINING

**6.1** The thickness of steel lining in tunnel depends upon:

a) minimum handling thickness,

b) that required for internal pressure after rock participation, and

c) that required for external pressure

**6.1.1** Regardless of pressure conditions, a minimum handling thickness is recommended for the shell to provide the rigidity required during fabrication. This is given by the formula:

$$t_{min} = (d + 800)/ 400$$

where

$t_{min}$ = minimum handling thickness in mm, and
d = internal dia of shell in mm.

**6.1.2** - For internal pressure, the sharing between rock and liner depends upon the modulus of elasticity of rock. The rock modulus may be determined by in situ tests and percentage of rock participation can then be calculated from 6.1.2.1.

**6.1.2.1** - The rock participation may be worked out from the following formula developed by patterson et al and is as given below:

$$\lambda = \frac{\sigma_t - \frac{E.r_o}{r}}{\sigma_t + P\left[\frac{E}{E_r}(1+\mu) + \frac{E}{2E_c} \times \frac{1}{r\,r_c}(r_c^2 - r^2) + \frac{E}{2E_r} \times \frac{1}{r_c d}(d^2 - r_c^2)\right]}$$

where

| | | |
|---|---|---|
| $\lambda$ | = | proportion of internal pressure transferred outside steel liner |
| $t$ | = | liner thickness in cm |
| $\sigma_t$ | = | allowable stress in steel liners |
| $E$ | = | modulus of elasticity of steel in kg/cm$^2$ |
| $r_o$ | = | initial gap between liner and concrete caused by shrinkage and creep of concrete and temperature effect |
| $r$ | = | inside radius of steel liner in cm |
| $P$ | = | internal pressure in tunnel kg/cm$^2$ |
| $E_r$ | = | modulus of elasticity of rock |
| $\mu$ | = | poisson's ratio of rock |
| $E_c$ | = | modulus of elasticity of concrete |
| $r_c$ | = | outside radius of concrete lining in cm and |
| $d$ | = | radius to the end of radial fissures in rock, that is, where the natural compressive stresses in the rock are just exceeded by the tensile stresses caused by internal pressure in cm. |

For the purpose of illustration two graphs have been prepared using the above formula, showing the variation of (i) rock participation factor ($\lambda$) vs gap width ($r_o$) and (ii) rock participation factor ($\lambda$) vs internal pressure (p). The graphs are given in Figs. 1 & 2.

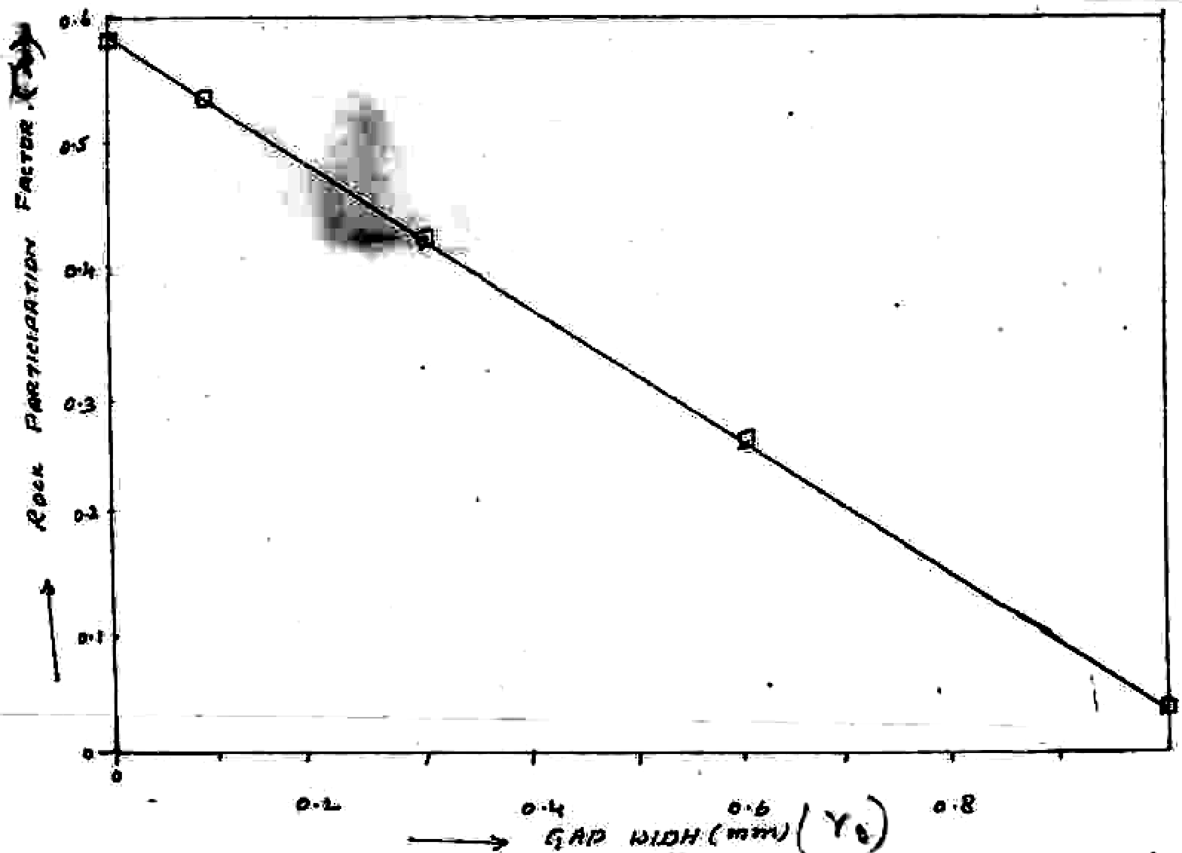


Fig 1 Rock Participation(λ) Vs Gap Width (Yo)

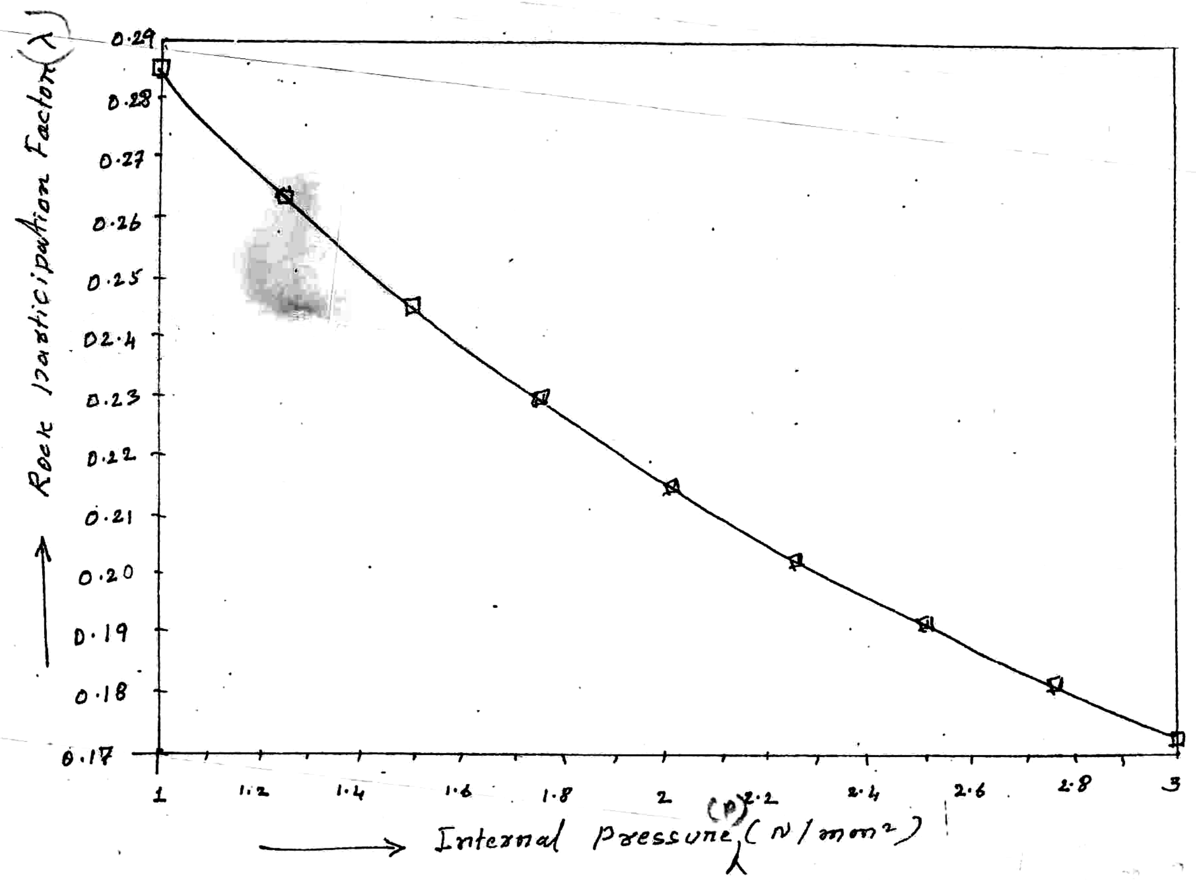


Fig 2 Rock Participation(λ) Vs Internal Pressure

**6.1.3** The thickness of steel lining should be determined for hoop stresses and checked for combined hoop and longitudinal stresses.

**6.2** The thickness of circular steel lining for internal pressure should be worked out by formula:

$$t = \frac{p.\ R}{s.\ e}$$

where

$t$ = shell thickness in cm,
p = maximum internal pressure after rock participation in kg/cm$^2$
r = inner radius of finished surface of tunnel in cm,
s = design stress in kg/cm$^2$
e = efficiency of longitudinal joint to be in accordance with 4.3.

**6.3 Shell Thickness due to External Water Pressure –** As regards to steel lining provided in tunnels the question of designing the steel shell for external pressure arises when water pressure develops around steel shell. Due to plastic yield in the rock, which may continue for considerable time, it is possible that a gap may be developed between steel and concrete or rock and also depends on the initial gap due to shrinkage of concrete and rock also depends on the initial gap due to shrinkage of concrete, temperature variation and plastic deformation of liner concrete and rock. Even though the rock would be grouted for some depth all around the periphery of the tunnel, the probability of water seeping through and accumulating in the cavity around the steel lining cannot be ruled out. Such water will be under pressure and would cause external pressure on steel lining. The shell thickness should be designed for external pressure or anchors can be provided.

**6.4 Designing the Shell for External Pressure –** The design of thickness of the shell is worked out by the standard formula, such as Barrot's/Amstutz's equation given at 6.4.1 and 6.4.2 respectively. However, a factor of safety of at least 1.5 shall be allowed over the calculated critical external pressure. Permissible critical external pressure can be increased by providing suitable anchors on the liner.

**6.4.1 Barrot's formula**

$$13\frac{P_c^2}{EK^2} + 2P_c\left(1 + \frac{K}{2} + \frac{6\Im}{KR^1} - \frac{F_e}{KE}\right) - \left(2F_e K - \frac{EK^2\Im}{R^1} - \frac{F_e^2}{E}\right) = 0$$

Where

| | | |
|---|---|---|
| $P_c$ | = | critical external pressure in kg/cm$^2$ |
| $E$ | = | modulus of elasticity in kg/cm$^2$ |
| $K$ | = | $t/R^1$ |
| $\Im$ | = | gap between steel lining and concrete in cm, |
| $R^1$ | = | external radius of curvature in cm, |
| $F_e$ | = | yield point stress in kg/cm$^2$, and |
| $t$ | = | thickness of shell in cm. |

### 6.4.2 Amstutz's equation

$$\left(\frac{f_n}{E^{'}}+\frac{\Im}{R^1}\right)\left[1+3K^2\frac{f_n}{E^{'}}\right]^{3/2}$$

$$=1.68\,K\frac{f_y^{'}-f_n}{E^{'}}\left[1-\frac{K}{4}.\frac{f_y^{'}-f_n}{E^{'}}\right] \text{.......(1), and}$$

$$1-\frac{PK}{2f_n}=0.175\frac{K}{E^{'}}\left(f_y^{'}-f_n\right) \text{...........(2)}$$

Where

| | | |
|---|---|---|
| $f_n$ | = | allowable stress in material in kg/cm$^2$ |
| $E^{'}$ | = | $E/\left(1-\mu_s^{\ 2}\right)$ |
| $\Im$ | = | gap between steel liner and concrete, in cm |
| $E$ | = | young's modulus of elasticity in kg/cm$^2$ |
| $f_y^{'}$ | = | $f_y/\left(\sqrt{1-\mu_s-\mu_s^2}\right)$ |
| $P_c$ | = | critical external pressure in kg/cm$^2$ |
| $f_y$ | = | yield stress of material in kg/cm$^2$ |
| $\mu_s$ | = | Poisson's ratio for steel |
| $K$ | = | $t/R^1$ |
| $R^1$ | = | external radius of curvature in cm |
| $t$ | = | thickness of shell in cm. |

**6.5 Protection –** Inner surface of the steel lining shall be provided with adequate protection against rusting by applying suitable paint.

## 7. DESIGN OF ANCHORS/ STIFFNER RINGS FOR RESISTING EXTERNAL PRESSURE

**7.1** In the present context anchors have a restricted role of resisting external pressures only. The anchors provided can be continuous along the circumference and placed at certain intervals. These can be made of either angle irons or latticed structure depending on the strength required. Stiffening provided should be simple and should not interfere with construction and proper placing and compaction concrete. Contact between the concrete and the steel lining should be complete.

**7.1.1** Spacing of anchors along the periphery of circular steel lining of a given thickness can be worked out by Backte's formula. The formula is as follows:

$$L = 2a.R$$

$$a = \frac{(F_{e1})^{3/2}\,.\,E\,.\,t^4}{P_c^{5/2}\ R^4}$$

Where

$L$ = spacing of anchors/stiffener rings in cm,
$F_{e1}$ = stress of lower yield point of steel in kg/cm$^2$,
$E$ = modulus of elasticity of steel in kg/cm$^2$,
$t$ = thickness of shell in cm,
$P_c$ = critical external pressure on the lining in kg/cm$^2$, and
$R$ = Internal finished radius of tunnel in cm.

**7.1.2** There is no method by which anchor/ stiffener ring spacing in the longitudinal direction can be determined. Hence, this is also kept the same as that along the circumference.

### 7.2 Size of Anchors/Stiffener Rings

**7.2.1** The function of anchor/stiffener rings is to sew the steel lining into concrete and thereby increase the number of bulges the steel lining shell should take due to external pressure.

**7.2.2** Anchor/stiffener rings should be therefore be strong enough not to be sheared off, should the steel lining shell try to slip along the concrete and should not allow all the inward bulges to concentrate at a single location.

**7.2.3** As a rough guide the anchors should be 25 to 40 mm in diameter and about 300 to 500 mm in length.

## 8. BANDS OVER STEEL LINING SHELLS

**8.1** It may not be posssible to provide steel lining for the designed thickness according to 7 due to non-availability of steel plates of required thickness or limitations due to fabrication difficulties. Steel bands are provided to share the load in steel shell, under such circumstances. Bands can also be used with advantage for strengthening the fabricated steel lining when rock at a particular location is found to be weaker than anticipated, after excavation.

## 9. CHANGE IN THE THICKNESS OF STEEL LINING

**9.1** The thickness of steel lining at different locations depends upon various factors enumerated in 6.1 to 6.4. Especially when the pressure tunnel or shaft passes through different layers of the rock, such as good medium or bad the steel thickness provided in bad or medium layer of the rock is extended into next better layer of the rock for a length equal at least to one diameter of the pressure tunnel or shaft. Beyond this the thickness is reduced in steps of not more than 5 mm each till the smaller thickness required for better rock is reached. These steps are kept at individual shells of fabricated smallest steps are kept at individual shells of fabricated smallest length. When the lining emerges from the tunnel it should be designed for full internal water pressure and due care should be taken of stress concentrations occurring in the surrounding rock.