भारतीय मानक

Indian Standard

IS 15026 (Part 2) : 2023

चट्टानों में सुरंग बनाना — दिशानिर्देश

भाग 2 टनल बोरिंग मशीनों द्वारा यंत्रीकृत टनलिंग विधियाँ

Tunnelling in Rock Masses — Guidelines

Part 2 Mechanized Tunnelling Methods by Tunnel Boring Machines

ICS 93.060

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Rock Mechanics Sectional Committee, CED 48

FOREWORD

This Indian Standard (Part 2) was adopted by the Bureau of Indian Standards, after the draft finalized by the Rock Mechanics Sectional Committee had been approved by the Civil Engineering Division Council.

Usage of tunnel boring machines (TBM) for tunnel excavation has increased across infrastructure sectors like hydropower, transportation and others. Compared to conventional tunnelling, tunnel boring machines limit disturbance to surrounding ground making it suitable for heavily urbanized areas as well as cost effective for longer tunnels which will require more time to complete using normal drill and blast techniques.

Tunnel boring machines perform full face excavation and mostly excavate circular cross-section of tunnels with diameters varying from 1 m to almost 15 m in variety of ground conditions and for various purposes. Excavation process produces a smooth tunnel wall after installation of precast segments. Cost of constructing a tunnel with tunnel boring machines is generally more than conventionally drilled tunnel in terms of cost per metre. However, tunnel boring machines give huge savings in terms of construction time through faster production rates.

Different types of tunnel boring machines suit different ground types. Hence, to ensure a reliable progress, it is of paramount importance to select and design tunnel boring machines suiting to ground, characterized through site investigations, topographical and hydrogeological surveys. Long and deep tunnels face different hazards and risks compared to tunnelling in shallow overburden.

The standard on tunnelling in rock masses IS 15026 was first published in 2002. In this revision, the tunnelling method in rock masses has been grouped into two parts. This standard (Part 2) covers guidelines for mechanized tunnelling methods. The other part being:

Part 1 Conventional tunnelling methods (*under prepration*)

This standard covers following important aspects:

a) Selection of tunnel boring machines;
b) Geological and geotechnical modelling;
c) Production aspects of segment lining;
d) Geotechnical risk management; and
e) Developments in TBM design to reduce squeezing ground risks.

This standard does not cover process management for design and manufacturing of TBM segments at this stage.

In the formulation of this standard due weightage has been given to international co-ordination among the standards and practices prevailing in different countries in addition to relating it to the practices in the field in this country. This has been met by deriving assistance from the following publications:

"Recommendation for Gasket Frames in Segmental Tunnel Linings" published by STUVA, Germany.

ITA COSUF N° 03 "Current Practice on Cross-Passage Design to Support Safety in Rail and Metro Tunnels" published by International Tunnelling Association (ITA), Switzerland.

ITA Report N° 22 "Guidelines for the Design of Segmental Tunnel Linings" published by International Tunnelling Association (ITA), Switzerland.

"Recommendation for the Selection of the Tunnel Boring Machine" published by German Tunnelling Committee (ITA-AITES), Germany.

The composition of the Committee responsible for the formulation of this standard is given in Annex E.

This standard contributes to the United Nations Sustainable Development Goal 9 'Industry, innovation and infrastructure' towards building resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; and Goal 11 'Sustainable cities and communities' towards making cities and human settlements inclusive, safe, resilient and sustainable.

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 : 2022 'Rules for rounding off numerical values (*second revision*)'. 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

TUNNELLING IN ROCK MASSES — GUIDELINES

PART 2 MECHANIZED TUNNELLING METHODS BY TUNNEL BORING MACHINES

1 SCOPE

This standard (Part 2) provides guidelines for construction of tunnels using mechanized tunnelling methods through tunnel boring machines (TBM) in soil and rock. The scope of this standard is to lay out the guidelines and provisions related to design and construction of TBM tunnels. This standard also defines guidelines for selection of type of TBM for tunnelling, geotechnical investigation, interpretation, characterization, properties and how they affect TBM tunnelling; manufacturing, durability and curing criteria for segmental lining, grouting in TBM lining; risk and mitigation measures related to TBM tunnels and construction of cross-passages in TBM tunnels.

2 REFERENCES

The standards listed in Annex A 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, and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of these standards.

3 GENERAL

Tunnelling by tunnel boring machine is a vast subject, with overlapping expertise from geotechnical, geological, civil, mechanical and urban planning. TBM tunnelling is a major form of mechanized tunnelling used across the globe and in India as well. The standard brings out various provisions and guidelines from past experiences and current practices for use of practising professional in the field of TBM tunnelling.

4 TYPES OF TBM AND THEIR SUITABILITY

Tunnel boring machines perform full face excavation. TBMs can be manufactured suiting to different diameters, ranging from micro TBM less than 1 m to TBM for large tunnels greater than 15 m. TBMs are available for different geological conditions ranging from hard rock to soft ground.

One of the requirements for use of a TBM is to have a detailed assessment of geology along the route of the tunnel. A universal machine suiting all types of rock and soil conditions does not exist (although TBMs with multiple modes of operation are being developed).

TBMs are classified based on mode of operation that is, open or closed (*see* Table 1). In closed mode, the excavation chamber of a tunnel boring machine is held under a measured and monitored positive pressure. The pressure is applied through slurry, remoulded earth or compressed air. Based on geological conditions, TBMs are operated in open or closed modes.

Table 1 Classification of Tunnel Boring Machines

(*Clause* 4)

Sl No.	TBM Type	Abbreviation	Operation Mode	
			Open	Closed
(1)	(2)	(3)	(4)	(5)
i)	Competent rock			
	a) Gripper	GRT	√	–
	b) Single shield/open shield	OPS	√	–
	c) Double shield	DOS	√	–
ii)	Soft ground/mixed geology/weak			

Table 1 (*Concluded*)

Sl No.	TBM Type	Abbreviation	Operation Mode	
			Open	Closed
(1)	(2)	(3)	(4)	(5)
	a) Slurry shield	SLS	√	√
	b) Earth pressure balance shield	EPB	√	√

Guidelines for areas of application and selection criteria for different TBM types are in Annex B.

Further advancement has been made into TBMs in terms of boring shape for projects with unique challenges. Since conventional circular TBMs cannot completely meet the requirements of underground space exploitation regarding the cross-section and space-utilization ratio, non-circular TBMs, which are the tunnelling equipment for an ideal cross-section, have become the new market growth point. List of non-circular TBMs available is provided below:

a) Double-O-tube, multi-circular face, and quasi-rectangular shield machines;
b) The rectangular TBM; and
c) The horseshoe shaped TBM.

5 GEOLOGICAL AND GEOTECHNICAL MODELLING

5.1 Characterization of Rock Mass

5.1.1 A key step is analysis of investigation results and geological interpretation followed by engineering characterization of rock mass and selection of suitable TBM.

5.1.2 Information collected through a series of surface geological mapping, drilling, test tunnelling or drifting, soil and rock mechanic testing must be interpreted and characterized so that the same could be used by the designers and for risk assessment. Additional drilling investigations may be planned at cross passage locations to have better assessment at these locations.

5.1.3 The standards IS 11315 (Parts 1 to 12), describe techniques and formats for collection of information on various parameters which are subsequently used in rock mass classifications.

5.1.4 Geophysical methods like electrical resistivity test and seismic refraction tests can be performed for both shallow and deep tunnels.

5.1.5 Rock mass classification systems RMR and Q, their broad impacts on underground openings are described in IS 13365 (Parts 1 and 2). These classifications are a part of engineering characterization of rock masses. Several empirical relationships are available for working out the properties such as modulus of deformation and shear strength through these systems. However, these empirical relationships are to be used with caution.

5.1.6 Hard ground and soft ground have a high impact on TBM design and progress. Particularly the strength and abrasivity of rock and their jointing pattern affect boring. Therefore, correct assignment of engineering properties to various geologic domains is of prime importance.

5.2 Testing for Rock Properties

5.2.1 *Uniaxial Compressive Strength* (*UCS*)

Uniaxial compressive strength test determined as per IS 9143 is the most basic property that describes the intact rock strength; and is measured by compression testing machine on rock cylinder samples. During TBM tunnelling, samples must be extracted from tunnel face and walls by portable drilling machines at a regular interval or when there is a change in lithology. With the variable advance rates in different geology, it is difficult to give an interval for regular testing, but it is suggested to test at every 500 m, minimum and when there is a change in rock type.

5.2.2 Other methods of strength determination may also be used such as point load test as per IS 8764, Schmidt's hammer test as per IS 12608 or geological hammer test from specialist literature.

NOTE — Special literature may include guidelines from International Society for Rock Mechanics (ISRM) or any other guidelines as per the agreements.

5.2.3 Other rock mechanic tests on laboratory rock samples for each rock type should be conducted. These tests are as given below:

a) *Physical properties* — Density, porosity, water absorption, hardness, slake durability; and
b) *Mechanical properties* — UCS Schmidt hammer test and point load index as above, modulus of elasticity, Poisson's ratio, tensile strength, shear strength.

5.2.4 For TBM tunnels certain specialized tests as per specialized literatures are recommended for each rock type as encountered in tunnel:

a) Mohs hardness and Vickers hardness;
b) Sievers J value;
c) Brittleness J value S20; and
d) Cerchar abrasivity index.

NOTE — Special literatures may include guidelines from International Society for Rock Mechanics (ISRM), (NTNU/SINTEF), (CAI) or any other guidelines as per the agreements.

5.2.5 Some of the analysis does require rock joint characteristics such as Joint stiffness which may be determined from rock cores from core drilling campaign or visible rock exposures in the surroundings.

5.2.6 Ideally 10 samples should be tested for each rock type for the various rock mechanic properties but minimum of 05 samples shall be required for each rock type.

5.3 Collection of Geological and Geotechnical Data during Construction

The geological model for a TBM tunnel is developed through a series of investigations during feasibility and investigation stages. By the time the project is put through bidding process, the base line geotechnical reports should be prepared. However, for detailed design if some additional testing is required, the same must be conducted prior to commencement of construction. It should be clearly understood that detailed investigations should be carried out during design stage and well before commencement of construction. Only confirmatory tests for detailed design as mentioned above may be conducted prior to construction.

On the other hand, there may be situations where supplementary tests are required even during the construction if there are substantial variations. Such cases need to be dealt carefully with the impact on project safety and timelines.

However, collection of geological data and rock classification is a part of tunnelling cycle and must be conducted for characterization of rock mass and efficacy or suitability of tunnel supports for various situations. Collection of data is different in case of open TBMs when compared to double shield TBMs where neither the face nor walls are visible. It has been experienced that the difficult ground conditions and extra ordinary geological conditions cause considerable hold-ups and extra cost particularly if conditions are not as predicted.

5.3.1 It should be noted that, for generation of geological data and preparation of maps, rock classification should be carried out prudently and accurately as number of activities such as installation of rock supports particularly in open TBMs is dependent on the same. In all types of TBM tunnels, geological records are to be preserved for reference when problems occur in the operation and maintenance stage. Such record shall be handy for undertaking repairs in future. On the other hand, these geological conditions often become a matter of dispute and therefore reliable and time-tested systems should be developed and implemented for generation and record of geological data.

5.3.2 Several types of TBMs are in use and every type of machine has different facilities for recording of data. In open type or main beam or shaft machines there is a gap between the cutter head and backup support systems. This opening is used for recording of geological data and preparation of 3D geological maps of the excavated surfaces. In the TBMs, it may be noted that it is not possible to record the face data continuously as the cutter head is in operation at the face. When the situation demands, cutter head may be retracted back for repairs or maintenance purposes during which face inspection is possible by entering through the cutter head window. However, such occasions neither are at regular intervals nor frequent to generate the geological information continuously. Rarely, cutter head may also be retracted solely for the purpose of geological inspection.

5.3.3 For documentation of rock conditions at the face, cutter head embedded with cameras could be used. Existing machines could also be upgraded with cameras for geological mapping. Qualified personnel study the pictures and develop the records therefrom. Such state-of-the-art devices be used to generate data in invisible areas which cannot be accessed for physical inspection.

5.3.4 For mapping of the walls, conventional 3D geological mapping with details of discontinuities together with recording of other parameters used for rock mass classification systems is required.

NOTE — In view of the severity of the site conditions, Engineer-in-charge may take a decision to perform other methods for collection of data required in **5.3.4.**

5.3.5 Duration of time consumed for geological mapping after each tunnelling cycle, may be decided as agreed to between the interested parties.

5.4 Post Construction phase

Wherever possible, relevant geophysical tests should be carried out post construction to capture impact of TBM tunnelling to mitigate risk of post construction damage to surrounding ground and built environment.

6 SEGMENTAL LINING

6.1 Types

Segmental lining can be of following types:

a) Re-bar reinforced cement concrete;
b) Steel fibre reinforced concrete;
c) Hybrid system (combination of reinforcement bars and steel fibers);
d) Any of the above with addition of synthetic fibres to cater for fire loads; and

e) Hollow steel segments for special locations along the tunnel.

Selection of lining types depend on project requirements and suitability.

6.2 Joints

TBM segment lining consists of circumferential and radial joints. Circumferential joints are formed at junction of two successive lining rings and radial joints are formed between various segments of same segment ring.

Depending upon segment shape, circumferential joints can be straight, tapered trapezoidal and tapered universal. Tapered universal ring is recommended for cases where there are horizontal and vertical curves along tunnel alignment as it gives flexibility for correction in tunnel alignment through ring sequencing. Other segment shapes shall be usedfor special design, construction, or project requirement.

Radial joints are flat or curved. They shall be chosen based on stresses permissible at the segment joints and thickness of segmental lining. Curved joints have advantage of avoiding damages due to ovalization but have higher steel requirements due to concentrated bursting stresses. The curved joints shall be followed in a project unless there is a special design, construction, or project requirement for flat joints.

6.3 Connections

The connections are made with assemblies associated with TBM segments. They shall be properly designed for structural and functional requirements as per IS 800. The assemblies are mentioned as below:

a) Gaskets or sealings;
b) Erector holes;
c) Lifting holes;
d) Segment connecting bolts/connectors and sleeves;
e) Thrust pressure distribution pads;
f) Dowels and guiding rods; and
g) Bolt and fastening system.

6.4 Sealings

To seal circumferential joints, elastomeric gaskets are placed around the segments like a frame near the lining extrados. It is important to select the right gasket material, profile geometry and groove geometry for a durable sealing over the service life of structure. Overall performance of sealings also depend upon complex interaction between dimensional tolerances of sealing material properties, segment production and ring installation (*see* Fig. 1).

6.4.1 *Types of Gaskets based on Fixity to Segment*

Glue-in gaskets are glued into gasket groove with a special adhesive after casting of segments. However, these gaskets can loosen or leave the groove during handling and installation of segments.

Anchored gaskets are placed inside the segment mould before casting of segments. Anchored gaskets provide higher bonding force through gasket legs embedded in concrete during segment production. These gaskets also provide an extended seepage path for water leakage during service life. Improper segment handling from production to installation stages may result in permanent unbinding of gasket from and may render the segments useless (*see* Fig. 2). Gaskets shall be re-inspected and repaired before segment installation

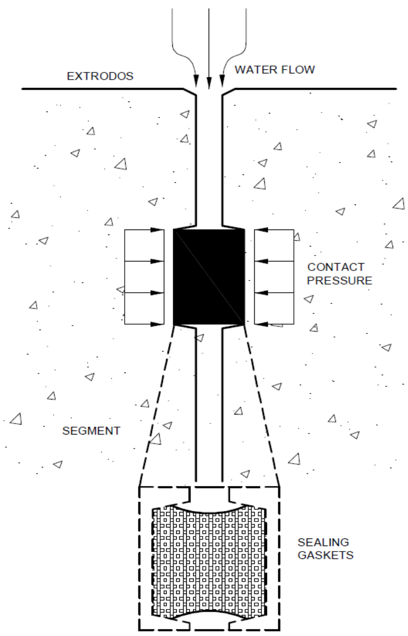


FIG. 1 SEALING MECHANISM OF GASKETED JOINTS IN SEGMENTAL LINING

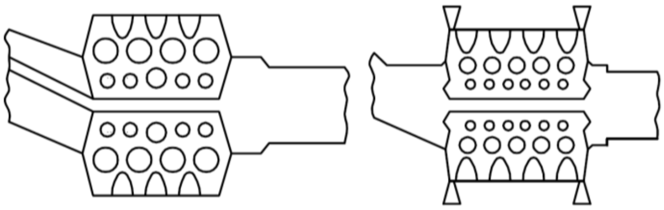


FIG. 2 REPRESENTATIVE ILLUSTRATION OF GLUE-IN AND ANCHORED GASKETS BASED ON FIXITY TO SEGMENT

6.4.2 *Types of Gaskets based on Affinity to Water*

Compressible gaskets are made of EPDM (ethylene propylene diene monomer) which achieves water tightness by compression of two gaskets of adjacent segments during ring assembly.

Hydrophilic gaskets are composite seals made of EPDM and a hydrophilic material which swells in the presence of water to ensure the designed water tightness. These can be either slotted hydrophilic or co-extruded hydrophilic type. Such gaskets require careful handling and storage as the hydrophilic material can swell before installation upon exposure to water/moisture and loose its effectiveness to swell post ring installation (*see* Fig. 3).

6.4.3 *Requirements and Testing*

Requirements for elastomeric material of gasket profiles and frames is recommended in Table 2 and Table 3. Compliance with these requirements shall be checked for initial acceptance and suitability testing.

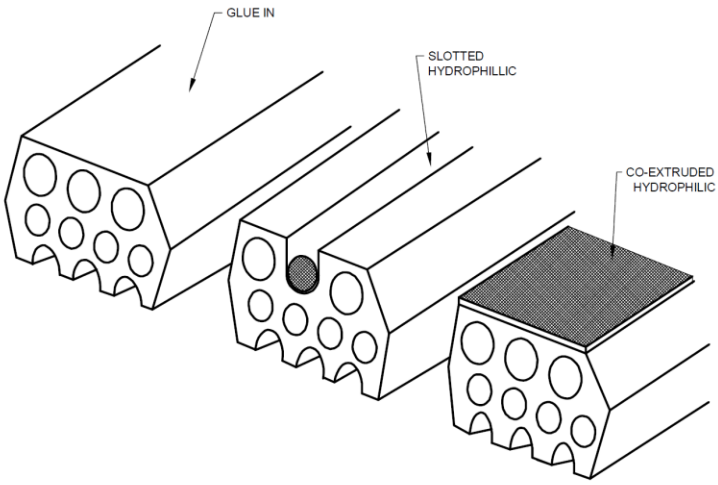


FIG. 3 REPRESENTATIVE ILLUSTRATION FOR DIFFERENT GASKETS BASED ON AFFINITY TO WATER

Table 2 Test Requirements for Elastomeric Material of Gasket Profiles and Frames

(*Clause* 6.4.3)

Sl No.	Type of Test	Requirement	Testing as per Indian Standard
(1)	(2)	(3)	(4)
i)	Profile tolerances	Class E2, *Min*	IS 16752
ii)	Material properties		
	a) Hardness b) Tensile strength c) Elongation at break	Stated value ± 5 IRHD ≥ 9 MPa *Hardness* — *Elongation at Break* 56 – 65 IRHD — ≥ 300 percent 66 – 75 IRHD — ≥ 200 percent 76 – 85 IRHD — ≥ 175 percent	IS 3400 (Part 2) IS 3400 (Part 1) IS 3400 (Part 1)
iii)	Compression set	≤ 20 percent	IS 3400 (Part 10/Sec 1)
iv)	Ozone resistance	No crack	IS 3400 (Part 20)
v)	Artificial ageing		
	a) Change of hardness, percent b) Change of tensile strength, percent c) Change of elongation at break, percent	– 5 percent to + 8 percent – 20 percent to + 10 percent – 30 percent to + 10 percent	IS 3400 (Part 2) IS 3400 (Part 1) IS 3400 (Part 1)
vi)	Stress relaxation, percent	≤ 45 percent	IS 3400 (Part 28)
vii)	Restorative capacity	≥ 90 percent	Refer specialist literature for test procedure
viii)	Deflection force for gasket frame and gasket corner	Refer specialist literature for test procedure and requirement	
ix)	Water tightness	Refer specialist literature for test procedure and requirement	

NOTE — Special literatures may include ISO 5893 : 2019 and STUVA recommendation or any other guidelines as per agreement between the parties.

In above Table 2, test for deflection force and water tightness are performed for suitability testing to groove geometry and water pressure. In water tightness test, water pressure shall be kept at least two times the design water pressure to cater for long-term relaxation.

Gasket manufacturing tolerances on profile height and width are normally for the tolerance class E2 as per IS 16752. However, tight tolerance class E1 may be specified for better performance (*see* Table 3). Profile width should be at least 1.6 times the profile height to prevent tilting of profile while erecting the ring.

For ozone resistance test as per IS 3400 (Part 20), recommended test conditions are given at Table 4.

Table 3 Allowed Tolerances for Profile Height and Width According to IS 16752

(*Clause* 6.4.3)

Sl No.	**Profile Height and Width,** in mm					
(1)	(2)					
i)	Class	≥ 10 to 16	≥ 16 to 25	≥ 25 to 40	≥ 40 to 63	≥ 63 to 100
ii)	E1	± 0.5 mm	± 0.7 mm	± 0.8 mm	± 1.0 mm	± 1.3 mm
iii)	E2	± 0.8 mm	± 1.0 mm	± 1.3 mm	± 1.6 mm	± 2.0 mm

Table 4 Test Conditions for Ozone Resistance Testing

(*Clause* 6.4.3)

Sl No.	Parameter	Value
(1)	(2)	(3)
i)	Ozone concentration	50 ± 5 pphm
ii)	Temperature	40 ± 2 °C
iii)	Prestress (conditioning)	72 + 0/– 2 h
iv)	Action time	48 + 0/– 2 h
v)	Strain at IRHD hardness 36 to 75 IRHD	20 % ± 2 %
	Strain at IRHD hardness 76 to 85 IRHD	15 % ± 2 %
vi)	Relative air humidity	55 % ± 5 %

6.4.4 *Gaps and Offsets*

Gap is the distance between concrete surface of adjacent segments after erecting a ring. Offset is mutual displacement of opposing gasket frames perpendicular to the gasket axis (*see* Fig. 4). Higher than designed gap or offset for a particular profile height and groove base distance reduces the compression force on the gasket, required to achieve specified water tightness.

Gaps and offsets result due to cumulative effect of tolerances on segment manufacturing and ring installation and the connection system used between adjacent segments. Gaskets should be tested for water tightness with extreme combination of gaps and offsets permitted during construction. 5 mm gap and 10 mm offset is generally defined as an upper limit at which segments should be installed.

6.5 Design Methods

Design of TBM segmental linings can be done through various methods. It is recommended to follow at least one method for preliminary design and at least two methods (with validation of results) for detailed design of the tunnel lining. Additional design methods (as given below) can be used to verify or optimize the design during construction and site-specific behaviour observed from instrumentation and monitoring data.

a) *Analytical approach*

   Curtis-Muir Wood method shall be used to carry out design.

b) *Numerical approach*

   Numerical modelling can be done on a numerical geotechnical model in 2D or 3D and/or a beam-spring model in structural model.

Continuum models are generally preferred for simplicity; although, discontinuum model can also be done for detailed analysis on case-to-case basis.

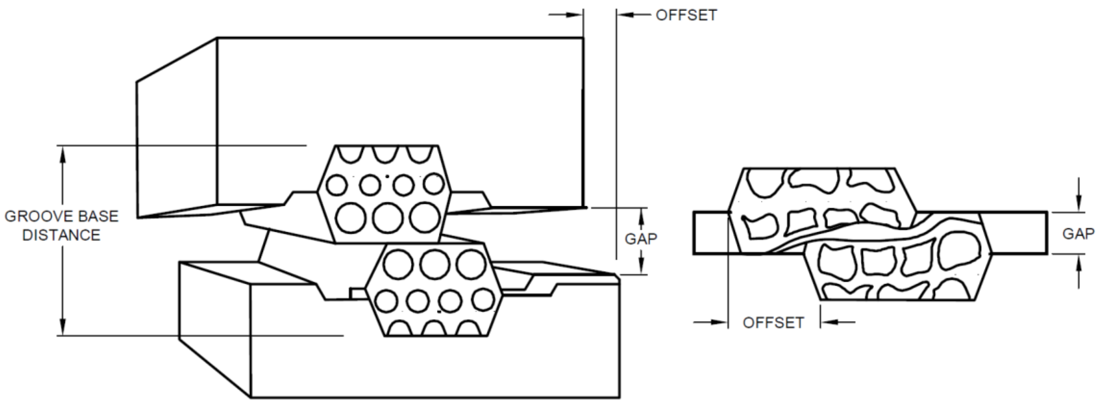


FIG. 4 ILLUSTRATION OF GAPS AND OFFSETS AT SEALINGS IN SEGMENTAL LINING

During the design process following parameters, in addition to general structural and geotechnical design criteria, shall be considered:

a) Allowable surface settlements and effects of liquefaction (short term, due to deflection of tunnel linings and long term).
b) Allowable volume loss – Recommended maximum allowable value for soft ground is 1 percent, however may vary as per geological conditions and impact on third party assets in the tunnel influence zone.
c) Building/utility damage assessment shall be carried out as per specialist literature.
d) Design shall be validated from instrumentation and monitoring results obtained during construction and optimization shall be done if required.
e) Design shall include the checks for estimated stresses due to fabrication, demolding, handling, storage/stacking, transportation, ring assembly/erection, floatation, and seismicity.
f) Design shall include splitting tensile checks due to thrust force from TBM jacks.
g) Design shall include checks for primary and secondary grouting.
h) Design shall include checks for stress concentration due to compression of waterproofing gaskets.
j) Design shall include checks of the bolts/inserts and their impact on TBM segment.
k) Load cases and load factors shall be as per relevant Indian standards or other international guidelines.
m) Design shall reduce the capacity of lining at joints due to discontinuity.

6.6 Manufacture of Precast Segments

6.6.1 *Concrete Mix Design*

Precast concrete segments remain in contact with ground during their entire service life and hence should be of required durability. Depending on exposure conditions, all concrete ingredients and concrete manufacturing shall be quality controlled in accordance with IS 456 and IS 10262. Development of mix design should be conducted well in advance considering exposure conditions during production and designed service life.

6.6.2 *Reinforcements*

Precast concrete segments are reinforced with steel reinforcement bars or fibres (steel or polypropylene) or a combination of both. When reinforced with only steel reinforcement bars, categorization is done as transverse (to resist main tunnel forces), longitudinal (to resist temperature and shrinkage) or joint/special reinforcement (to resist forces from TBM Jacks or at vicinity of joints). Reinforcement spacing shall allow fixing of built-in-parts in the segment mould before casting. Segment design shall specify permitted rebar/reinforcement bar cage placement tolerances.

For an improved post-cracking flexure strength, crack control and overall economy, fibre reinforcements should be used for design and manufacture of precast concrete segments, in accordance with specialist literature supported with field testing. Adoption of design with reinforcement bars, fibres or hybrid solution should be confirmed against specified performance requirements through full scale bending test of casted precast segment. Production and testing shall continue throughout segment casting to demonstrate that the specified performance is being achieved. Testing of concrete shall demonstrate that the fibres are uniformly distributed throughout the concrete mix.

6.6.3 *Fire Resistance*

During tunnel fire, thermal gradients develop in concrete lining which result in spalling due to thermal expansion of concrete due to restraint and buildup of water vapour pressure. One method to provide fire resistance is addition of micro-polypropylene (PP) fibers with dosage 1 kg/m^3 to 2 kg/m^3 of concrete which significantly reduces risk of spalling. Micro PP fibers melt before reaching temperature of 160 °C providing channels for escape of water vapour. Full scale fire testing may be performed on precast concrete segments to determine dosage for ensuring performance under complex scenarios. For more details, guidance from IS/ISO 834 (Parts 1 to 9) may be taken. Minimum nominal cover of 40 mm shall be provided for 4 h fire resistance as per IS 456.

6.6.4 *Curing of Segments*

Depending on project requirements for faster production, steam curing shall be considered. Precast segments are steam cured in static or carousel-based segment production method, to achieve required demoulding strength (depending on design check for segment) within 8 h of casting. Steam curing shall be done at 100 percent relative humidity and maximum steam temperature limited to 70 °C. During application/discontinuing of the steam curing, the ambient air temperature shall change at a rate not exceeding 22 °C per hour. Generally, duration of steam curing at peak temperature is kept between 6 h to 8 h. Trials shall be done to ascertain correct duration of steam curing, to achieve desired concrete strength.

Generally, 2 h to 4 h after placing concrete and after the concrete has undergone initial set, the first application of steam should be made, unless retarders are used, in which case the waiting period before application of the steam should be increased to 4 h to 6 h. Water curing methods to be used from the time concrete is placed until steam is first applied. Adding hot water in cold weather facilitates curing as well as reduces thermal gradient inside concrete segment during steam curing. Temperature monitoring may be documented for checking adverse effects of high curing temperature.

Post demoulding, curing compound shall be applied as an alternate to further water curing of concrete ensuring complete personal protection equipment. The segment surface temperature during application of curing compound should not be more than atmospheric temperature by 20 °C.

6.6.5 *Durability of Precast Segments*

Durability of concrete precast segments should be ensured to meet requirements of load bearing capacity of the ring and its individual components, water tightness under designed ground water pressures, avoiding spalling and excessive degradation due to corrosion of reinforcements or aging of concrete by carbonation over the designed life period.

6.6.5.1 *Design life and crack width*

Precast segments are not easily repairable or serviceable and hence designed for minimum 100 year service life. Crack widths should be limited to less than 0.2 mm during design and subsequently during service stage. Precautions shall be taken to avoid thermal cracking of concrete during casting.

6.6.5.2 *Carbonation of concrete and chloride/ sulphate attack*

Mostly durability is affected due to carbonation of concrete and severe exposure towards sulphate attack from ground water on reinforcements, amongst others. Maximum acid soluble chloride content shall be limited to 0.4 kg/m^3 and water soluble sulphate content expressed as SO_3 shall be limited to 4 percent by mass of cement as per IS 456. However, provision of minimum concrete cover of 40 mm on intrados and extrados of precast concrete segments for steel reinforcement bars shall be followed.

6.6.5.3 *Concrete permeability of concrete*

Maximum depth of water penetration shall be restricted to 10 mm for a sample prepared and tested at design ground water pressure as per IS 3085 for 72 h.

6.6.5.4 *Chloride ion penetration*

Chloride attack poses a significant threat to reinforced concrete especially for structures that are likely to be exposed to high concentrations of salts. Chloride attack results in corrosion of steel reinforcement, leading to cracking and spalling of concrete. Resistance to chloride ion permeability is important to prevent attack on steel reinforcements. Maximum chloride permeability rating shall be specified depending upon project exposure conditions; however, no individual test result shall exceed 1 000 coulombs at concrete age of 28 days. For test methods and frequency of chloride ion penetration testing, special literature may be referred.

NOTE — Special literature may include ISO 1920 (Part 11) : 2013 'Testing of concrete: Part 11 Determination of the chloride resistance of concrete, unidirectional diffusion' or any other guidelines as per the agreements.

6.6.5.5 *Alkali silica reaction* (*ASR*)

ASR is a heterogeneous chemical reaction which takes place in aggregate particles between the alkaline pore solution of the cement paste and silica in the aggregate particles. All aggregates shall be tested for alkali silica reaction as per IS 2386 (Part 7) and deleterious content as per IS 2386 (Part 2). The aggregates should be innocuous for alkali reactivity and shall have deleterious content limited to 2 percent by mass. *See* also IS 383.

6.6.5.6 *Delayed ettringite formation* (*DEF*)

DEF is expansion and cracking of concrete associated with the delayed formation of the mineral ettringite which is a normal product of early cement hydration. DEF should be prevented by limiting the internal concrete temperature to 70 °C during its early life.

6.6.5.7 *Numerical assessment of design life*

Various softwares are available to assess design life of structures using inputs of concrete quality and properties of surrounding environment and provide the design life of structure as output. These techniques shall be adopted to ensure the desired design life of structure.

6.7 Quality Control in Precast Concrete Segment Production

Quality control is required to establish reasonable confidence in the performance of the concrete mix and its constituents to deliver the required performance throughout the design life of the structure. Projects may define their own frequency and specific requirements; however, testing is conducted for initial suitability and confidence in control over continuous production process.

A quality control plan shall list out all factors responsible for influencing quality of concrete as well as Initial suitability and production process.

Testing for concrete shall be carried for checking concrete compressive strength, splitting tensile strength, flexure strength, permeability and other tests related with durability as per IS 456 and requirements stated in **6.6.5** of this standard to the extent applicable.

6.7.1 *Dimensional Control for Segment Moulds*

Tolerance to mould dimensions shall be agreed with manufacturer during design of each mould catering to temperature variations and number of casting cycles expected at segment casting yard. After fabrication, dimensional accuracy (angles, distances, and torsion) shall be ascertained before using them for factory production. After being reused, say for 30 times post commissioning of casting factory, each mould shall be rechecked for dimensional accuracy. Subsequently, during continuous production, each mould shall be rechecked for dimensional accuracy at every 200 reuses and readjusted if necessary. Allowable tolerances to mould dimensions during any stage of check are recommended in Table 5.

6.7.2 *Fabrication Control and Installation Tolerance for Precast Segments*

These are allowable deviations from design dimensions in casted segments or from designed installation geometry, which do not result in damage to the segmental lining or rendering it unusable for the intended function. Segment design should always be checked for tolerances comprising of fabrication and installation tolerances separately for both individual segments and complete ring.

6.7.2.1 *Fabrication tolerance*

Fabrication tolerances for every segment for first 10 castings from a new mould should be measured and subsequently, say for every 50th casting. Recommended fabrication tolerances for precast segments are provided in Table 6.

Table 5 Allowable Tolerances to Mould Dimensions

(*Clause* 6.7.1)

Sl No.	**Description of Mould Dimension**	**Tolerance**
(1)	(2)	(3)
i)	Width	± 0.5 mm
ii)	Developed length between lateral surfaces	± 1.0 mm
iii)	Thickness	± 1.0 mm
iv)	Maximum distortion	± 1.0 mm
v)	Distance between radial face and supports of angle template	± 0.2 mm
vi)	Roundness of mould bottom	± 1.0 mm
vii)	Position of inserts and block-outs between rings and segments	± 1.0 mm

Table 6 Fabrication Tolerances for Precast Segments

(*Clause* 6.7.2.1)

Sl No.	**Description**	**Tolerances based on Inner Ring Diameter**	
		≤ 8.0 m	≥ 11.0 m
(1)	(2)	(3)	(4)
i)	Longitudinal joints tolerances (based on the load transfer surface)		
	a) Longitudinal joint deformation	± 0.3 mm	± 0.5 mm
	b) Angular deviation of the longitudinal joint	± 0.5 mm	± 0.7 mm
	c) Addition rule of 1.1 and 1.2	± 0.6 mm	± 0.9 mm
ii)	Overall segment deviations (based on the median plane)		
	a) Segment width	± 0.5 mm	± 0.7 mm
	b) Segment thickness	± 3.0 mm	± 4.0 mm
	c) Segment arch length	± 0.6 mm	± 0.7 mm
	d) Inner radius of each segment	± 1.5 mm	± 2.5 mm
	e) Difference of the diagonal length of a segment to the target length	± 1.0 mm	± 2.0 mm
	f) Vertical spacing of the fourth segment corner from the plane formed by the other three corners	± 5.0 mm	± 8.0 mm

Table 6 (*Concluded*)

Sl No.	Description	Tolerances based on Inner Ring Diameter	
		≤ 8.0 m	≥ 11.0 m
(1)	(2)	(3)	(4)
iii)	Sealing groove		
	a) Sealing groove width	± 0.2 mm	± 0.2 mm
	b) Sealing groove depth	± 0.2 mm	± 0.2 mm
	c) Position of sealing groove axis	± 1.0 mm	± 1.0 mm
iv)	Flatness of the contact zones		
	a) Longitudinal and ring joint	± 0.3 mm	± 0.5 mm
v)	Tolerances on the entire segment ring		
	a) Outside diameter	± 10 mm	± 15 mm
	b) Inside diameter	± 10 mm	± 15 mm
	c) Outer circumference (measured at three heights)	± 30 mm	± 45 mm
vi)	Position of the fixing components		
	a) Erector cones	± 2.0 mm	± 2.0 mm
	b) Spiral pockets and bushings	± 1.0 mm	± 1.0 mm

NOTES

1 Interpolate the values for inner ring diameter between 8 m and 11 m.

2 Individual maximum tolerances are not allowed to add up and go beyond tolerances on entire segment ring.

3 In the case of inconsistency between two dependent tolerances, the more stringent shall be adopted.

4 Relaxation in tolerances for gasket groove shall be in accordance with the requirements of the gasket supplier/gasket type after ensuring performance for specified conditions.

5 Tolerances on the entire segment ring relate to the tolerances of the master ring only. For these any two rings shall be erected on a flat and level base with the top ring rotated one bolt pitch from the bottom ring with the bolts inserted. The base ring shall be retained as the master ring. Checks shall be made against the master ring at intervals not exceeding 1 in every 200 produced rings.

6.7.2.2 Dimensional control measurement records of individual segments and ring sets preferably after segment striping should be maintained as per project requirement. Laser based measurement of moulds and segment which deliver a complete 3D geometry check to detect deviations in the sub-millimetre range may also be employed. Tolerances on complete ring can be measured by physically placing one ring on top of another ring or comparing digitized models of ring geometry generated by a laser interferometer with the theoretical ring geometry.

6.7.2.3 *Installation tolerances*

Deviations from design ring geometry can be observed due to inaccurate ring installation. Excessive deviation from installation tolerances lead to reduced advance rates, joint misalignments, reduced sealing performance and overall functional performance of the segment (*see* Table 7).

Table 7 Recommended Installation Tolerances for Segment Rings

(*Clause* 6.7.2.3)

Sl No.	Description of Inaccuracy	Recommended Range
(1)	(2)	(3)
i)	Maximum shape ovalization on diameter	
	a) For inner diameter up to 8 m	± 0.25 percent of ID
	b) For inner diameter more than 8 m	± 0.50 percent of ID
ii)	Maximum ring roll (absolute)	± 100 mm
iii)	Maximum ring roll (relative)	± 10 mm
iv)	Joint offset/steps or lips	± 5 mm to ± 10 mm
v)	Maximum gap between joint contact faces	± 5 mm
vi)	Tolerance on absolute vertical position of segment invert	± 75 mm
vii)	Planarity of faces of the ring	± 0.75 mm from theoretical plane

Table 8 Recommended Remedial Measures for Damage Repair during Segment Production
(*Clause* 6.8)

Sl No.	Damage Type	Description	Remedial Measure
(1)	(2)	(3)	(4)
i)	Voids	Small voids visible on surface	Closure of voids by stopping with cement-bound mortar and final surface smoothing.
ii)	Cracks	Cracks with more than 0.2 mm opening	Penetration can be done with epoxy resin. Cracks less than 0.2 mm can be penetrated with glue.
iii)	Spalling	Separation of concrete layer from segment normally near the groove or segment edges	Post forming with cement mortar and final forming for spalling of less than 5 mm depth and/or less than 20 m length. Spalling greater than 30 mm will need epoxy resin for reconstructing original geometry.
iv)	Breakage	Within groove, contact areas, near erector cones or bolting gaps	Upto 8 mm depth and 50 mm length breakage can be repaired with closure of voids by stopping with non-shrink cement-bound mortar and final surface smoothing.
v)	Pockets	Locally limited and do not reach reinforcement	Reach intact concrete zone and fill with non-shrink cement-bound mortar.

6.8 Damages of Concrete TBM Segmental Linings

Damages to concrete TBM segment lining can occur during production, transportation, ring building and TBM advancing. Some of the production defects and their recommended remedial measures are provided in Table 8.

7 ANNULUS GROUTING

Annulus grouting is the construction method to fill up the annular gap between tunnel excavation and installed segmental lining. Backfill grout ensures homogenous contact of installed segment lining with the ground, controls further ground movement and surface settlement due to volume loss at shield, stabilizes segmental lining in the ground and improve its water tightness. Grout should be pumpable to the point of injection without segregation or bleeding, for the required distances and time. Grout should attain adequate strength to not de-bond from surrounding ground.

7.1 Grout Mixes

7.1.1 Based on reactivity, mortar-based grout mix can be divided into three categories:

a) *Active* — Full hydration of binder component occurs. Portland cement content is normally more than 200 kg/m^3 in active mixes.
b) *Semi-inert* — Minor hydration of binder takes place. Portland cement content varies between 50 kg/m^3 to 200 kg/m^3.
c) *Inert* — No binder content is present.

Selection of type of grout depends on project requirements like risk of settlement, future deformation allowance, machine downtime during no operation and ground conditions.

7.1.2 Based on number of components, grout mix can be divided into following categories.

7.1.2.1 *Single component*

Mixture of sand, binder like cement or lime, water and plasticizer which should be sufficiently workable from time of mixing to injection to ensure pumpability of mix. All components are transported to back system of TBM through vehicles which requires detailed logistics planning.

7.1.2.2 *Two component*

Achieves better filling of annular void compared to single component but requires more sophisticated equipment and maintenance to prevent clogging of injection nozzles. Two components are referred to as A/B grouts where component A is a stable mortar filler comprising of cement, Bentonite, water, etc; and component B is hydration accelerating liquid like sodium silicate, etc mixed to component A at point of injection. Both components are transported through pipes and have easy logistics. Site trials should be conducted to demonstrate complete penetration of grout behind installed segment lining for the selected mix proportions (*see* Table 9).

Table 9 Benefits of Single and Two Component Grout Mix

(*Clause* 7.1.2.2)

Sl No.	Consideration	Single Component	Two Component
(1)	(2)	(3)	(4)
i)	Strength	√	–
ii)	Cost	√	–
iii)	Transportation	–	√
iv)	Dilution due to groundwater	–	√
v)	Early set time	–	√
vi)	Early support	–	√
vii)	Fluidity	–	√
viii)	Batching	–	√
ix)	Maintenance	–	√

7.1.2.3 *Pea gravel*

In case of hard rock geology, annular gap can also be backfilled with pea gravel (washed gravel with diameter 8 mm to 12 mm mostly round and without any fines) for immediate stabilization of segment lining. Pea gravel is pneumatically pumped through segment holes or blow pipes which fills annulus at angle of repose. Subsequently, voids in pea gravel are filled with cement grout through secondary grout operation.

7.2 Grouting

7.2.1 Primary annulus grouting can be conducted through channels provided in the tail shield (*see* Fig. 5) and/or through holes in the segment lining.

a) When grouting through tail shield, multiple rows of tail seal brushes, preferably made of steel, are filled with grease to close the gap between the shield tail and segment lining extrados and protect against entry of ground water, grout, etc. The pressure of grease is always maintained above the pressure of annulus grout.

b) When grouting through holes provided in segment lining, there is higher risk of settlement as annular gap remains unfilled for a longer time.

7.2.2 Secondary grouting is performed through holes in segment lining and required to fill voids left after primary annulus grout. Void detection behind segment lining can be performed randomly at crown portion with geophysical tests like ground penetrating radar, etc. The secondary grout pressures shall be assessed with respect to the capacity of segmental lining against stresses generated due to localized pressures and resulting ovalization. Monitoring of lining deformation resulting from secondary grouting shall be done during and post activity.

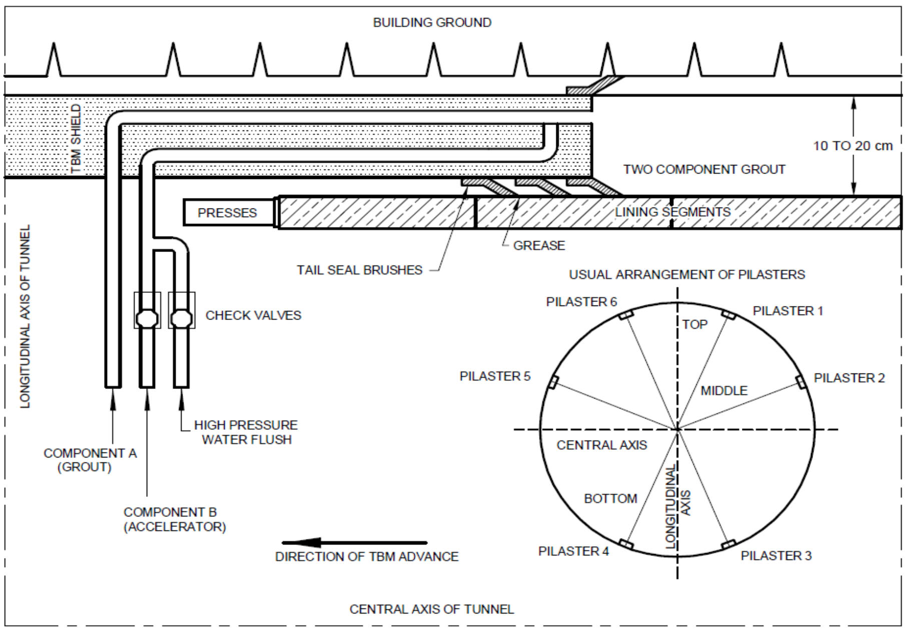


FIG. 5 ANNULUS GROUTING THROUGH TAIL SHIELD

8 PRINCIPLES FOR DESIGN AND CONSTRUCTION OF CROSS PASSAGES

8.1 Cross-passages are essential elements of twin-tube railway and road transit tunnels. During construction and operation, cross-passages serve multiple functions. For the operation phase of a tunnel, major requirements result from the unique needs of normal, maintenance and emergency mode of tunnel operation.

8.2 During an emergency, cross-passages contribute significantly to the safety of tunnels by providing an escape route for the tunnel users from the incident to the non-incident tube, that is, to a safe area, and by providing an access route for emergency forces from the safe area to the incident tube. Cross-passages need to be designed such that smoke or hazardous gases may not propagate into or through the cross-passages to protect the safe area in the non-incident tube. During normal operation, the cross-passages shall house and protect technical equipment of various technical systems (for example, low voltage power supply, data/communication installations, etc). During maintenance, the cross-passages shall support a safe working environment for staff.

8.3 Selection of Cross-passage Shape as Per Ground Condition

8.3.1 The geometry of the cross-section of cross-passage are important to identify as per geological and loading condition for safety and economical design. The shape of the cross-section depends on the external and internal forces acting on the perimeter of the excavated profile as detailed in Fig. 6.

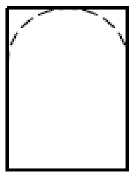
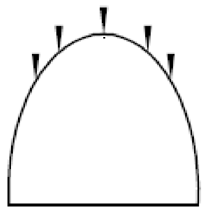
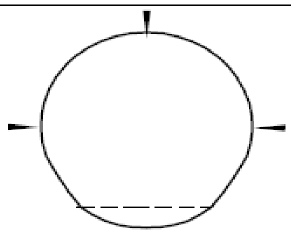
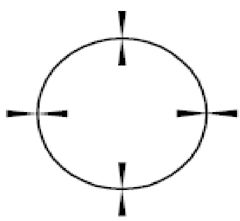
SHAPE	APPLICATION
 RECTANGULAR / D-SHAPE	USED WHEN THE EXTERNAL FORCES DO NOT LEAD TO ANY DAMAGING MOVEMENT OF THE ROCK MASS INTO THE TUNNEL.THIS KIND OF TUNNEL IS SELF-STABLE. THIS KIND OF SECTION IS VERY SUITABLE FOR CONSTRUCTION PURPOSE.
 SEMI-ELLIPTICAL,PARABOLLIC, OR SEMI-CIRCULAR	USED WHEN ONLY VERTICAL FORCES ACT AND THERE IS MOVEMENT INTO THE TUNNEL AT CROWN
 HORSESHOE, VAULTED	USED WHEN VERTICAL AND HORIZONTAL BOTH THE FORCES ACT SIMULTANEOUSLY. THIS KIND OF SECTION IS GIVEN ADVANTAGE FOR ACCOMODATION OF UTILITY SERVICES AND BETTER HEAD ROOM.
 CIRCULAR	USED WHEN FORCES ACT FROM ALL THE SIDES. THIS KIND OF SHAPE ARE COMMONLY USED FOR SOFT-GROUND CONDITION AND UNDER-WATER TUNNELS

FIG. 6 BASIC CROSS-SECTION SHAPES OF CROSS PASSAGES

8.4 Location and Dimension

8.4.1 Where tunnels are provided in twin tube configuration, cross passages to the adjacent tube can be considered a safe refuge. The cross passage should be of at least 2 h fire resistance rated construction, and should be equipped with self-closing fire rated doors that open in both directions. Distance between any two cross-passageways and other design requirement should be as per SP 7 (Part 4). Special literature may also be referred depending upon the project requirement. The system shall incorporate a walking surface or other approved means for passengers to evacuate a train at any point along the train way so that they can proceed to the nearest station or other point of safety. Cross-passageways shall be a minimum of 1 200 mm in clear width and 2 100 mm in height, if intended of only pedestrians. Larger cross passages may be required for movement of emergency vehicles as per project requirements.

NOTE — Special literatures may include guidelines from NFPA 130 or any other guidelines as per the agreement(s).

8.5 Design Considerations

8.5.1 Cross-passages are used to be designed in railway and road infrastructure for both soil and rock condition. In exceptional cases, cross-passages are used to be designed by the Box-Pushing Method in soil condition. For detailed design of cross-passage and support arrangements IS 15026 (Part 1), IS 456 or special literature can be followed. Load combinations for design shall be adopted as per SP 7 (Part 6), and project requirements.

NOTE — Special literatures may include guidelines from Indian Road Congress, (IRC) SP-91, FHWA-NHI-09-010 and ITA-COSUF N° 03 "International Tunnelling Association" or any other guidelines as per the agreement(s).

8.5.2 During the design of opening for cross passage in railway or road transit system where TBM segment have been used, the load in tunnel lining from which the segments are removed, is transferred to the adjacent fully enclosed rings, as illustrated in Fig. 7.

8.5.3 Permanent disruption to the structural response of nearby segmental lining and re-distribution of soil effective stresses will happen at the opening area where cross-passages will be constructed. This creates additional stresses on the nearby segments at opening area which should be safely distributed to other structural elements. The segments located at opening of cross-passage must be designed to withstand all load cases and combinations which they will be subjected during their design life. In deciding upon the type of the temporary opening support systems, it is important to review the geological and geotechnical parameters through additional investigations as per site feasibility for safe and economical design. The ovalization acceptance criteria of the segments at the opening location shall be decided as per the project requirement considering the Schedule of Dimension (SOD). The approach for junction design of cross-passage can be analysed using analytical and numerical methods of design.

8.5.4 Different temporary support systems are available to create an opening on the precast concrete segments. Temporary steel bracing can be installed inside of tunnel at opening space to provide support and mitigate ring ovalization resulting from opening and cross passage excavation. Commonly used systems are mentioned in Fig. 8 to Fig. 11.

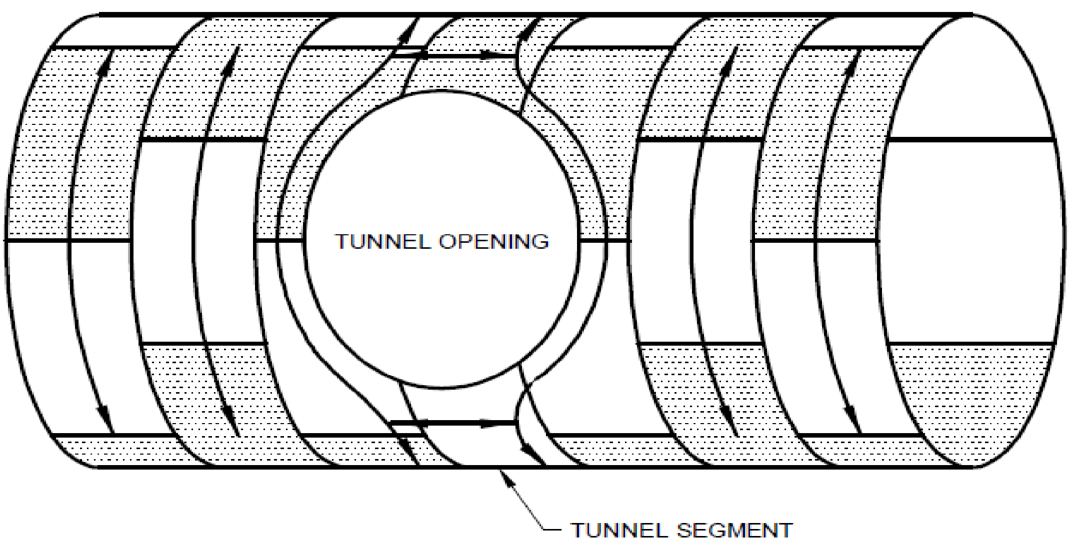


FIG. 7 STRESS DISTRIBUTION AROUND OPENING IN SEGMENTAL LINING

FIG. 8 STEEL LINTEL AND SILL BEAMS IN CONJUNCTION WITH STEEL PROPS

FIG. 9 HALF-MOON SUPPORT FRAME

FIG. 10 FULL-MOON SUPPORT FRAME

FIG. 11 PREFABRICATED STEEL SEGMENTS

8.6 Precautions for Cross Passage Construction

Problems encountered during cross-passage construction and precautions required are given as below.

8.6.1 *Ingress of Water and Proper Assessment of the Ground Condition*

Water can inflow through rock-joints during construction of opening for cross-passage if water level is high, which can cause difficulty in cross-passage construction. Adequate preparedness for fillings of the joints with grouting arrangement shall be readily available. The ground condition shall be accurately assessed to minimize the risk of failure. These issues may cause chimney formation and an unsafe working environment. Probe-drilling shall be done before opening for cross-passage from safety aspect.

8.6.2 *Inadequate Design and Construction Scheme*

Inappropriate support arrangement and construction scheme can trigger the risk for failure of cross-passage. It is to be ensured before construction that the support systems are in order as per the ground and loading condition.

8.6.3 *Material and Equipment Issue*

Use of construction material and equipment with inadequate properties may lead to failure of cross-passage. Suitable quality material and equipment as per project specifications shall be used.

8.6.4 *Delay in the Installation of Support System*

The delay in the installation of support system may lead to failure in critical ground condition. Skilled person shall be deployed at site to take decision instantly upon observing the criticality of the ground condition to minimize the risk of failure. The materials and equipment shall be in place to carry out the task as per drawings, construction methodology and specifications.

9 FACE PRESSURES

If the ground is unstable, weak enough with high deformations than desired or groundwater exist at the tunnel face with undesirable water inflow, then it should be kept under pressure. The pressure in the work chamber should be kept at a level that allows stable working conditions. If it is too low an uncontrolled collapse into the chamber could occur and if it is high, it may cause a 'blow out' or deformation of the ground surface.

10 URBAN TUNNELLING AND ITS ADDITIONAL REQUIREMENTS FOR TUNNEL DESIGN

10.1 Ground and Sub-Surface Displacements

Ground and subsurface displacements shall be considered as an important criterion in design and construction of tunnel. The settlement shall be calculated with empirical approach. The estimation of displacement shall be verified with analytical and numerical approaches.

During construction, ground movement records and controls shall be put in place. Various limits on ground movement shall be defined as per design, and demarked with colors such as green, amber and red as per the severity of ground movement. The data collected on ground movements during construction shall be used to correlate with design values and validation/review of design shall be carried out, if required.

10.2 Tunnelling Induced Vibrations

All tunnel induced vibrations shall be within limits to have minimum impact on the state of structural health of third-party structures/buildings in the influence zone of construction.

10.2 Tunnelling Induced Vibrations

The limits of maximum ground vibration allowed on buildings are mentioned below:

Building Class	*Type of Structure*	*Frequency* Hz	*Vibration Limits* mm/s
I	Industrial reinforced concrete and steel buildings and structures	10 – 60 60 – 90	30 30 – 40
II	Buildings with concrete foundations and floors; Underground structures	10 – 60 60 – 90	18 18 – 25
III	Buildings with concrete foundations and basement floor, wooden floors and brickwork walls	10 – 60 60 – 90	12 12 – 18
IV	Buildings sensitive to vibrations or requiring protection	10 – 60 60 – 90	8 8 – 12

Additional limits of vibration for special cases are as below:

Case	*Maximum Allowed Limit* mm/s
For water supply, gas supply and fuel supply pile lines	5
Inside the residential/office buildings	5

Detailed study on vibration impact for sensitive cases not listed above, shall be done in accordance with IS/ISO 4866.

10.3 Groundwater Contamination

Groundwater contamination during construction shall be within the limits as specified in the project specifications, local guidelines and laws.

11 INSTRUMENTATION AND MONITORING

Main objective of instrumentation and monitoring are to:

a) obtain information on ground response due to tunnelling;
b) provide construction control;
c) verify design parameters and analysis;
d) measure performance of support system during and after construction;
e) assessment of groundwater impact due to tunnelling from environmental aspect; and
f) indicate a warning of critical ground condition due to tunnelling.

The quantity and frequency of instruments and monitoring shall be based on ground response and same shall be adopted as per project requirement.

IS 17446 provides the details of instrumentation and monitoring of tunnels, special literature may be referred for the details.

NOTE — Special literatures may include guidelines from ITA tech report N° 03 "International Tunnelling Association" or any other guidelines as per the agreement(s).

12 GEOTECHNICAL RISK MANAGEMENT

Geotechnical risks are always part of tunnelling, however for successful TBM tunnelling, it is important to undertake detailed ground investigations to identify all hazards and then consequently selection and design of an appropriate TBM. Long and deep tunnels face different hazards compared to tunnelling in shallow overburden. Few identified geological hazards for different TBM types along with identification of consequences on the selected TBM and location of the hazard are given in Annex B. Recommendations for mitigation measures for various hazards depending on selected TBM are given in Annex D. List of hazards and mitigation measures presented in Annex C and Annex D are just for guidance purpose and need to be updated to the project requirements. These mitigation measures shall not be construed to reduce importance of detailed investigations during initial project stages.

12.1 Geotechnical Risk Mitigation Measures

12.1.1 *Advance Probing*

Advance probing is used in difficult ground conditions to predict indication of water ingress, gas potential, fault, and transition zones. Both direct and indirect methods are used for this purpose. Direct methods require to drill an investigation hole ahead of tunnel face whereas indirect methods use geophysics to provide data regarding strata ahead of face.

12.1.1.1 List of direct methods for advance probing are presented in Table 10. Direct investigations are conducted by drilling ahead of TBM head with or without core recovery. Systematic probing with an overlap of 5 m to 10 m is mandatory to correctly predict the strata likely to be encountered for TBM boring through difficult ground conditions.

12.1.1.2 List of indirect methods for advance probing are presented in Table 11. Indirect investigations are non-destructive methods, conducted by using geophysical methods. These methods require less time for probing; however, they cannot replace application of direct methods completely. Commonly used geophysical methods are based seismic wave velocity and electrical resistivity of the ground ahead of cutter head. Depending on ground properties, appropriate Geophysical methods can be used to predict ground conditions. However, selective confirmation of interpretation by core drilling is recommended.

Table 10 Direct Methods for Advance Probing Ahead of TBM Face

(*Clause* 12.1.1.1)

Sl No.	Investigation Type	Description
(1)	(2)	(3)
i)	Boreholes with core recovery	Horizontal boreholes are made through cutter head with a rig positioned behind the TBM cutter head. Preventer valves are utilized to prevent ingress of water during drilling. This method is not commonly used due to low speed, interruption to TBM boring and higher associated costs. Length of probing is restricted to under 10 m due to huge time for investigations. Geotechnical tests on rock samples can be performed on extracted cores of NX size.
ii)	Boreholes without core recovery	Both horizontal and inclined boreholes can be done through the ports provided in the cutter head and behind it through the shield respectively through a drilling hammer and extension rods. Diameter of hole is restricted to 75 mm, however greater lengths of 40 m or more are possible within short span of time. Measure while drilling parameters like penetration rate, percussion pressure, rotation pressure, etc are captured to interpret the strata to be encountered. In large diameter tunnels, usually up to 2 to 3 probe drills are required depending upon variability of the ground. Measurement while drilling (MWD) parameters from probe drills can be corelated with TBM boring parameters to have good interpretation of Geology.

Table 11 Indirect Methods for Advance Probing Ahead of TBM Face

(*Clause* 12.1.1.2)

Sl No.	Type of Test	Description
(1)	(2)	(3)
i)	Seismic methods	This technique is one of the main methods for non-destructive, long-sighted prediction ahead of tunnel face, usually up to 5 to 10 times tunnel diameter. Short holes are drilled on the tunnel walls and the small blasts are taken in them to generate seismic waves. Part of wave signal is picked up by high precision equipment receiver mounted on the walls. Excavation is stopped while performing this test.
ii)	Geo-electric methods	This technique relies on the induced polarization method. The system is attached on head of TBM, and it continuously generates two sets of data for resistivity and percent frequency effect that have correlations with water content in rock mass and fractures/TBM advance rates, usually 2 to 4 times tunnel diameter. This technique is more successful in detecting water bodies ahead of face. Excavation is not stopped while performing this test.

12.1.2 *Ground Conditioning*

The following describes several techniques that can be used to improve the stability of the ground to aid construction of the tunnel, reduce/control ground displacements and hence mitigate the effects of the tunnelling operation on adjacent structures.

12.1.2.1 *Lowering groundwater table*

In permeable strata where the permeability, *k*, exceeds about 10^{-3} cm/s, or where an aquifer can be dewatered below less permeable strata, the level of the water table over a wide area can be drawn down by pumping from boreholes and deep wells.

There are two principle methods of groundwater lowering: well points and deep filter wells. Well points, although one of the most versatile methods of dewatering, are limited to dewatering to a depth of about 6 m (limited by the effective vacuum lift of a pump), although staged well points can be used to go deeper, but a greater excavated plan area is required. Well points are installed at between 1 m to 3 m intervals by wash boring, that is, using high pressure water jetting to form the borehole, but the spacing depends on the permeability of the ground. Well points can also be used from inside the tunnel, in this case they should be directed upwards.

Drawdown of the groundwater level can cause consolidation settlements in the surrounding ground and hence affect adjacent structures, and therefore it shall be closely monitored. The extent of the drawdown zone depends on the depth of the well and the type of ground.

Further assessment on groundwater lowering and dewatering shall be done as per specialized literature. Further complicated cases shall be modelled in numerical/analytical models for detailed study.

12.1.2.2 *Pre-grouting*

Major types of grouting used in tunnelling are as follows:

a) Permeation grouting (chemical grouting),
b) Jet grouting, and
c) Compaction grouting.

The design of grout shall be followed by a test at field before implementation during construction. The desired properties of the strata shall be worked out during design and various design mix of grouts shall be tried during field test. The samples from field shall be properly tested (minimum 3 samples) and at least 2 samples must achieve the desired properties.

Further, post grouting, the test shall be repeated across the grouted area to validate the assumptions made in design.

12.1.2.3 *Pressurized tunnelling* (*compressed air*)

The disadvantage of constructing a tunnel under air pressure is that, in order to maintain the air pressure at the face, all the materials and spoil, as well as the workforce, have to be passed through an airlock system. The maximum working pressure and the time that workforce can spend working in compressed air shall be strictly controlled.

Project shall consider health and safety requirements related to exposure of workers to conditions where the pressure is higher than atmospheric. Effects of both compression and decompression shall be included. Work plan shall clearly specify the procedures to follow safe working.

The design shall consider the risk and mitigations for blowouts. The provisions shall also be incorporated in the design.

12.1.2.4 *Ground freezing*

The freezing method is only applicable when the ground contains water, ideally still, fresh water. A ground with a moisture content greater than 5 percent shall be considered for this technique.

Water can be added using a fire hose, a sprinkler system, a borehole or injection device to raise the moisture content in the ground.

Frozen areas shall overlap to provide an impermeable barrier. Cooling fluid shall be brine (salt solution) with a temperature of – 50 ºC to – 20 ºC or liquid nitrogen which evaporates at – 196 ºC.

Ground heave can occur and shall be included as a criterion for design and the impact of heaving on the nearby structures shall be assessed. Heaving shall be limited under acceptable limits by controlling the speed of the freezing process and/or the sequence of freezing.

There are two methods of ground freezing:

a) *Two phase method* (*closed*) — In this method, a primary refrigerant (ammonia or freon) is used to cool a secondary fluid (usually brine); and
b) *Direct process* (*open*) — In the direct process liquid nitrogen is used to freeze the ground. The nitrogen is passed down the freeze pipes and then allowed to evaporate into the atmosphere. This direct process is good for short-term or emergency projects. Liquid nitrogen is likely to be the only effective method for freezing pore water in fine grained soils.

When designing the freezing system, the thermal characteristics of the ground to be frozen and the freezing point of the groundwater shall be determined. The process shall be carefully monitored during construction. Thermocouple strings shall be used to monitor the ground temperatures between the freezing elements and to monitor the refrigerant temperature.

Ground freezing shall be carried out as per specialist literature.

12.1.3 *Developments in TBM Design to Reduce Squeezing Ground Risks*

Squeezing ground conditions risk TBM operations, when deformations occur which close gap between shield and surrounding excavated rock. Converging tunnel face puts additional load on the cutter head requiring a higher torque for rotation. In TBMs with low thrust/torque capability, this leads to jamming of shield or cutter head due to friction. TBM jamming usually occurs in shielded rock TBMs with high *in-situ* stresses and soft ground conditions. Following measures may be adopted based on project requirements to mitigate TBM squeezing risks.

12.1.3.1 *Enlargement of boring diameter by increasing radial overcut*

In squeezing ground conditions, additional space around TBM shield should be provided to allow ground relaxation by deforming without squeezing the shield. Increased radial overcut can be achieved by shimming the periphery cutters, increasing diameter of periphery cutters and installing additional cutters at guage positions. Typically, a uniform radial overcut of up to 100 mm can be provisioned in TBM during design stage.

12.1.3.2 *Cutter head offsetting*

By design, diameter of cutter head is kept slightly bigger than diameter of connecting end of front shield by 50 mm to 100 mm. Typically, in squeezing ground conditions, deformations are observed mostly in tunnel crown, hence TBM cutter head should have provision to move cutter head vertically up. Vertical cutter head offsetting is used together with boring diameter enlargement to increase radial overcut at crown.

12.1.3.3 *Conical shield*

During TBM excavation, deformation in tunnel wall occurs behind TBM shield as TBM advances ahead. Based on most frequent ground properties and condition of *in-situ* stresses, deformation values can be easily estimated. A conical shield having larger front shield diameter and lesser tail shield diameter can be provisioned during TBM design to cater for deformation which is bound to happen most of times. The rate of conicity from front to tail shield may be kept in range of 5 mm to 10 mm (calculated on the diameter) per meter of shield. If not estimated properly, conicity can unnecessarily increase TBM cutting diameter and consumption of annulus grout behind segmental lining leading to overall increase in construction cost.

12.1.3.4 *Lubrication of TBM shield extrados*

To reduce skin friction at points of contact between rock and shield, provision to lubricate shield extrados with bentonite or similar material should be made during design stage. This lowers skin friction coefficient and reduces the torque and thrust requirement of TBM during advancement.

12.1.3.5 *Sufficient torque and thrust*

Squeezing zones should be excavated by adopting all measures as stated above, however when jamming of TBM shield or cutter head occurs due to circumstances beyond control at site, then additional thrust and torque can help to rescue and release the shield from converging ground.

12.1.3.6 *Convergence monitoring devices on TBM shield*

Convergence monitoring device comprises of steel cylinders fixed inside front shield which can be pushed outwards towards excavated rock when TBM is not advancing. When these cylinders are provided at ring width spacing, they can measure deformation at same location 3 times or more. This helps in knowing the deformation trends during each ring building cycle and helps in strategizing additional measures to prevent shield jamming due to squeezing ground.

13 E AND M (ELECTRICAL AND MECHANICAL) AND VENTILATION

Ventilation systems shall be design by both empirical and analytical approaches.

13.1 Empirical approach may be based on:

a) Emergency ventilation smoke control in roadways tunnels; and
b) Vehicle emission and air demand for ventilation in road tunnels.

For railway tunnels the emissions expected during operation shall be converted to equivalent truck numbers and above guidelines shall be used. For empirical approach special literatures may be used.

NOTE — Special literatures may include guidelines from AASHTO, PIARC or any other guidelines as per the agreements.

13.2 Analytical approach may be based on CFD (computational fluid dynamics) analysis and SP 7. Special literatures may also be referred.

NOTE — Special literatures may include guidelines from UIC 779-9R, TSI-SRT, and NFPA 130 or any other guidelines as per the agreements.

14 USE OF ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML) IN TBM TUNNELLING

14.1 Artificial Intelligence and machine learning are ongoing developments in many industries including tunnelling. These technologies shall be carefully included in the projects with inclusion of processes and provisions in the project requirements. The local guidelines/laws for use of these technologies shall be adhered to.

14.2 Data-driven automation in project may result in issues related to data security. Each project is unique and has its own challenges related to who can collect the data, how to store it, how to ensure its security, who owns the data during project and after completion of project, who has access to data and during which stage of the project. This control over data shall be defined by client and controls must be defined in detail. Therefore, it shall be integral for projects to embrace the best and right data management environment for implementation of AI. Such a data management environment will offer greater security to sensitive data and make it simple for projects to access siloed data for AI and ML projects.

14.3 Since AI and ML use in a project has challenges, it is important to understand specific and clear conditions for following:

a) Specific provisions on collection, storage and processing the data;
b) Specifying the restricted access to relevant data to concerned users at various stages of project that is, setting up a system to provide users with access to relevant data only at a particular stage of project;
c) Specifying the control on data and defining controls with respect to the project stages;
d) Specifying the security standards for data security;
e) Clearly specifying the requirement for processing the data and related use of systems required for the same;
f) Specifying the outputs from programs;
g) Defining the allowed error in output expectations from the programs;
h) Specifying the ownership of data and/or AI/ML program; and
j) Specifying training requirements for use of data and program.

ANNEX A

(*Clause* 2)

LIST OF REFERRED STANDARDS

IS No.	*Title*
IS 383 : 2016	Coarse and fine aggregate for concrete — Specification (*third revision*)
IS 456 : 2000	Plain and reinforced concrete — Code of practice (*fourth revision*)
IS 800 : 2007	General construction in steel — Code of practice (*third revision*)
IS/ISO 834	Fire-resistance tests elements of building construction:
(Part 1) : 1999	General requirements
(Part 4) : 2000	Specific requirements for load bearing vertical separating elements
(Part 5) : 2000	Elements of building construction
(Part 6) : 2000	Specific requirements for beams
(Part 7) : 2000	Specific requirements for columns
(Part 8) : 2002	Specific requirements for non-load bearing vertical separating elements
(Part 9) : 2002	Specific requirements for non-load bearing ceiling elements
IS 2386	Methods of test for aggregates for concrete:
(Part 2) : 1963	Estimation of deleterious materials and organic impurities
(Part 7) : 1963	Alkali aggregate reactivity
IS 3085 : 1965	Method of test for permeability of cement mortar and concrete
IS 8764 : 1998	Method of determination of point load strength index of rocks (*first revision*)

IS No.	*Title*
IS 9143 : 1979	Method for the determination of unconfined compressive strength of rock materials
IS 10262 : 2019	Concrete mix proportioning — Guidelines (*second revision*)
IS 11315	Method for the quantitative description of discontinuities in rock masses:
(Part 1) : 1987	Orientation (*under revision*)
(Part 2) : 1987	Spacing (*under revision*)
(Part 3) : 1987	Persistence (*under revision*)
(Part 4) : 1987	Roughness (*under revision*)
(Part 5) : 1987	Wall strength (*under revision*)
(Part 6) : 1987	Aperture (*under revision*)
(Part 7) : 1987	Filling (*under revision*)
(Part 8) : 1987	Seepage (*under revision*)
(Part 9) : 1987	Number of sets (*under revision*)
(Part 10) : 1987	Block size (*under revision*)
(Part 11) : 1985	Core recovery and rock quality designation (*under revision*)
(Part 12) : 1992	Drill core study (*under revision*)
IS 12608 : 1989	Method or determination of hardness of rock
IS 13365	Quantitative classification system of rock mass — Guidelines:
(Part 1) : 1998	RMR for predicting engineering properties

IS No.	*Title*
(Part 2) : 2019	Rock mass quality for prediction of support pressure, support system and engineering properties in underground openings (*first revision*)
IS 15026 (Part 1) : 2022	Tunnelling methods in rock masses — Guidelines: Part 1 Conventional tunnelling methods (*under preparation*)
IS 17446 : 2020	Observational method for tunnelling in rock masses — Guidelines
IS 16752 : 2018 ISO 3302-1 : 2014	Rubber — Tolerances for products — Dimensional tolerances
IS 3400 (Part 1) : 2021/ISO 37 : 2017	Methods of test for vulcanized rubber: Part 1 Tensile stress-strain properties (*fourth revision*)
IS 3400 (Part 2) : 2014/ISO 48 : 2010	Methods of test for vulcanized rubber: Part 2 Determination of hardness (Hardness between 10 IRHD and 100 IRHD) (*fourth revision*)
IS 3400 (Part 10/Sec 2) : 2020/ISO 815-1 : 2014	Methods of test for vulcanized rubber: Part 10 Compression set, Section 2 At ambient temperatures (*second revision*)
IS 3400 (Part 20) : 2018/ ISO 1431-1 : 2012	Methods of test for vulcanized rubbers: Part 20 Resistance to ozone cracking — Static strain test (*second revision*)
IS 3400 (Part 28) : 2022/ISO 3384-1 : 2019	Methods of test for rubber, vulcanized or thermoplastic: Part 28 Determination of stress relaxation in compression — Testing at constant temperature
IS/ISO 4866 : 2010	Mechanical vibration and shock - vibration of fixed structures — Guidelines for the measurement of vibrations and evaluation of their effects on structures
SP 7 : 2016	National building code of India, 2016

ANNEX B

(*Clauses* 4 *and* 12)

AREAS OF APPLICATION AND SELECTION CRITERIA FOR DIFFERENT TBM TYPES

B-1 RECOMMENDED AREA

The recommended area of application for various TBMs is provided in Table 12.

B-1.1 Recommended selection criteria for different TBM types for application in soil and rock on basis of relevant geotechnical parameters is provided in Table 13 and Table 14. These tables are provided only for common guidance and actual selection criteria of TBM type may depend on project specific requirements. In the table, (√) denotes main application area, (o) denotes limited application area and (x) denotes application not recommended.

Table 12 Areas of Application for various TBM Types

(*Clause* B-1)

Sl No.	Type of TBM	Abbreviation	Areas of Application Soil	Areas of Application Rock
(1)	(2)	(3)	(4)	(5)
i)	Gripper	GRT	Not recommended	*See* Table 13
ii)	Double shield	DOS	Not recommended	*See* Table 13
iii)	Single shield	OPS	*See* Table 14	*See* Table 14
iv)	Slurry shield	SLS	*See* Table 14	*See* Table 14
v)	Earth pressure Balance shield	EPB	*See* Table 14	*See* Table 14

Table 13 Areas of Application for Gripper (GRT) and Double Shield (DOS) TBM

(*Clause* B-1.1)

Sl No.	Parameter	Application on Rock						
(1)	(2)	(3)						
i)	Unconfined compressive strength (MPa)		0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
		GRT	x	o	√	√	√	√
		DOS	o	o	√	√	√	√
ii)	Rock quality designation (RQD)		0 – 25		25 – 50	50 – 75	75 – 90	90 – 100
		GRT	x		o	√	√	√
		DOS	o		√	√	√	√
iii)	Rock mass ratio (RMR)		< 20		21 – 40	41 – 60	61 – 80	81 – 100
		GRT	x		o	√	√	√
		DOS	o		√	√	√	√
iv)	Water inflow per 10 m tunnel (l/min)		0		0-10	10-25	25-125	> 125
		GRT	√		√	√	o	x
		DOS	√		√	√	o	x
v)	Abrasivity (CAI)		0.1 – 0.5		0.5 –1	1 –2	2 – 4	4 – 6
		GRT	√		√	√	o	o
		DOS	√		√	√	o	o
vi)	Swelling potential		None		Poor	Fair	High	
		GRT	√		√	o	o	
		DOS	√		√	o	o	
vii)	Confinement pressure [bar]		0		1 – 4		4 –7	7 –15
		GRT	√		x		x	x
		DOS	√		x		x	x

Table 14 Areas of Application for Single Shield Open (OPS), Slurry Shield (SLS) and Earth Pressure Balanced Shield (EPB) TBM

(*Clause* B-1.1)

Sl No.	Parameter	Application on Soil					
(1)	(2)	(3)					
i)	Fines content (< 0.06 mm)		< 5 percent	5 – 15 percent	15 – 40 percent	> 40 percent	
		OPS	x	x	x	o	
		SLS	√	√	√	o	
		EPB	x	o	o √	√	
ii)	Permeability (m/s)		$> 10^{-2}$	10^{-2}-10^{-4}	10^{-4}-10^{-6}	$< 10^{-6}$	
		OPS	x	x	x	o	
		SLS	x	o	√	o	
		EPB	x	x	o	√	
iii)	Consistency		Very soft 0 – 0.5	Soft 0.5 – 0.75	Stiff 0.75 – 1.0	Very stiff 1.0 – 1.25	Hard 1.25 – 1.5
		OPS	x	x	x	x	o
		SLS	x o	o	o	o	o
		EPB	o	√	√	o	o
iv)	Relative density		Dense	Medium Dense	Loose		
		OPS	√	x	x		
		SLS	√	√	o		
		EPB	√	√	√		
v)	Confinement pressure (Bar)		0	1 – 4		4 – 7	7 – 15
		OPS	o	x		x	x
		SLS	o	√		√	√
		EPB	√	√		o	x
vi)	Swelling potential		None	Little	Fair	High	
		OPS	√	√	o	x	
		SLS	√	√	o	x	
		EPB	√	√	o	x	
vii)	Abrasivity (equivalent quartz content) percent		0-5	5 – 15	15 – 35	35 – 75	75 – 100
		OPS	√	√	√	o	o
		SLS	√	√	√	o	o
		EPB	√	√	o	o	x
Application on Rock							
viii)	Unconfined compressive strength (MPa)		0 – 5 5 – 25	25 – 50	50 – 100	100 – 250	> 250
		OPS	o o	√	√	√	√
		SLS	o o	O	o	o	o
		EPB	o o	O	x	x	x
ix)	Rock quality designation (RQD)		0 – 25	25 – 50	50 – 75	75 – 90	90 –100
		OPS	o	√	√	√	√
		SLS	o	O	o	o	o
		EPB	√	O	o	x	x
x)	Rock mass ratio (RMR)		< 20	21 – 40	41 – 60	61 – 80	81 –100
		OPS	o	√	√	√	√
		SLS	o	o	o	o	o
		EPB	√	o	o	x	X

Table 14 (*Concluded*)

Sl No. (1)	Parameter (2)	Application on Soil (3)					
xi)	Water inflow per 10 m tunnel (l/min)		0	0 – 10	10 – 25	25 – 125	> 125
		OPS	√	√	√	o	x
		SLS	o	o	o	o	o
		EPB	o	o	o	o	o
xii)	Abrasivity (CAI)		0.1 – 0.5	0.5 – 1	1 – 2	2 – 4	4 – 6
		OPS	√	√	√	o	o
		SLS	√	√	o	o	o
		EPB	√	√	o	o	x
xiii)	Swelling potential		None	Poor	Fair	High	
		OPS	√	√	o	o	
		SLS	√	√	o	x	
		EPB	√	√	o	x	
xiv)	Confinement pressure [bar]		0	1 – 4		4 – 7	7 – 15
		OPS	√	x		x	x
		SLS	o	√		√	√
		EPB	o	√		o	x

ANNEX C

(*Clause* 12)

COMMON GEOLOGICAL HAZARDS IN TBM USAGE

C-1 GEOLOGICAL HAZARDS

The common geological hazards along with consequence level and identification of consequences on the selected TBM is given in Table 15.

Table 15 Hazard and Consequences for the Selected TBM Type

(*Clause* C-1)

Sl No.	Hazards	Consequence Level			Identification of Consequences on TBM	Location		
(1)	(2)	(3)			(4)	(5)		
		Open	**Single shield**	**Double shield**	0 Not concerned 1 Negligible — No further consideration of the hazard is needed 2 Unwanted — Risk mitigation measures shall be identified. The measures shall be implemented if the costs of the measures are not disproportionate with the risk reduction obtained 3 Unacceptable — The risk shall be reduced at least to unwanted, regardless of the costs of risk mitigation	**Tunnel face**	**TBM area**	**Back-up area**
i)	Spalling	0	0	2	Blocking of the telescopic part of the shield	-	√	-
		2	0	2	Gripper bracing difficulties	-	√	-
		0	1	1	Cracks in the segmental lining	-	-	√
		1	0	0	Damage of the support	-	-	√
		2	0	0	High cleaning effort in invert (time consuming)	-	√	√
ii)	Rock-burst	3	3	3	Damage of TBM	√	-	-
		2	2	2	Damage of the cutter head and/or the cutting tools	√	-	-
		3	3	3	Injuries of the workers during face inspections	√	-	√
		0	2	2	Damage of the segmental lining	-	-	√
		2	0	0	Damage of the support	-	-	√
		3	0	0	Injuries to workers	-	√	√
		3	0	0	Damage of the back-up; Damage of the belt conveyor	-	√	√
iii)	Squeezing and buckling	2	2	2	Jamming of the cutter head	√	-	-
		1	2	3	Jamming and damage of the shield	-	√	-
		2	0	0	Jamming and damage of the back-up	-	-	√
		0	3	3	Overstress of the segmental lining	-	-	√
		2	0	0	Overstress of the support	-	-	√
		3	0	0	Inadmissible high tunnel convergences	-	-	√

Table 15 (*Concluded*)

Sl No.	Hazards	Consequence Level			Identification of Consequences on TBM		Location		
(1)	(2)	(3)			(4)		(5)		
		Open	**Single shield**	**Double shield**	0	Not concerned	**Tunnel face**	**TBM area**	**Back-up area**
					1	Negligible — No further consideration of the hazard is needed			
					2	Unwanted — Risk mitigation measures shall be identified. The measures shall be implemented if the costs of the measures are not disproportionate with the risk reduction obtained			
					3	Unacceptable — The risk shall be reduced at least to unwanted, regardless of the costs of risk mitigation			
iv)	Extremely high-water inflow	2	2	2	Reduction of advance rate up to stop		-	-	-
		3	3	3	Complete stop of the TBM due to site flooding		-	-	-
		2	2	2	Mucking-out difficulties		-	√	√
		0	2	2	Difficulty in bedding the segment		-	√	√
		3	3	3	Hazardous working conditions		√	√	√
v)	High water pressure	2	2	2	Damage of the support or segmental lining		-	-	√
		2	2	2	Damage of the drilling equipment		-	-	√
vi)	Mud inrush	3	3	3	Complete stop of the TBM due to site flooding		√	√	-
		3	3	3	Hazardous working conditions		√	√	√
		2	2	2	Mucking-out difficulties		√	√	√
		2	2	2	Cleaning problem		√	√	√
vii)	Face instability	2	2	2	Block of the cutter head		√	-	-
		2	2	2	Damage of the cutter head and/or the cutting tools		√	-	-
		1	3	3	Injury of workers during inspection and maintenance		√	-	-
		2	2	2	Overstress of the support or the segmental lining (due to stress redistribution)		-	-	√
		2	2	2	Damage of belt conveyor due to large or sharp-edged blocks destroying the belt and/or the transfer chutes		√	√	√
viii)	High temperature	3	3	3	Difficult to unacceptable working conditions		√	√	√
		1	2	2	Where mortar & shotcrete must be installed, quick grout hardening could happen		√	√	-

ANNEX D

(*Clause* 12)

EXAMPLES OF MITIGATION MEASURES FOR GEOLOGICAL HAZARDS

D-1 MITIGATION MEASURES

The examples of mitigation measures for various geological hazards and difficulty in implementation based on the selected TBM shall be as given in Table 16.

Table 16 Mitigation Measures Regarding the Consequences of the Hazards duringTBM Operation According to the Selected TBM Type

(*Clause* D-1)

Sl No.	Hazards	Difficulty Level to Implement			Example of Mitigation Measures	
(1)	(2)	(3)			(4)	
		Open	Single Shield	Double Shield	0	Not concerned
					1	Easy to implement on site, to be previously considered in the design
					2	Medium difficulty of implementation
					3	Exceedingly difficult to implement
i)	Spalling	0	0	1	Selection of the appropriate type of the telescope to limit the material accumulation and prevent blockage	
		0	0	2	Operation of the double shield TBM as a single shield TBM	
		0	2	2	Improvement of the annular void filling method to stabilize the ring as early as possible	
		1	0	0	Installation of radial bolting (friction anchors) in combination with wire mesh and Shotcrete	
		1	1	1	Appropriate torque reserve (high torque low speed gear)	
ii)	Rock-burst	1	1	1	Execution of sub-horizontal destructive drilling combined with blasting around the perimeter of the TBM	
		1	2	0	Drilling of large diameter holes (approximately 100 mm), as close as possible to the cutter head	
		1	1	1	Avoid front loading cutter head; change cutter tools from inside (back-loading cutter head)	
		1	1	1	Avoid face inspections or work in front of the cutter head in risk zone	
		1	1	1	Install face inspection cameras and wear cutters tools	
		1	0	0	Presence of workers in the machine zone (0–2 diameters) should be avoided	
iii)	Squeezing and buckling	1	1	1	Advance exploration with sub-horizontal probe drilling with registration of parameters and geophysics	
		1	1	1	Non-stop operations (requiring modification of the shift system)	
		1	2	2	Increase the radial over-cutting (and consequently the annular gap around the shield)	
		0	1	1	Appropriate shield geometry (conical shape, reduction of the shield length)/Avoid use of double shield TBM	
		1	1	1	Lubrication of the shield extrados	
		1	1	1	Installation of a high thrust force – with sufficiently high factor of safety (overdesign)	
		1	1	1	Appropriate torque reserve (high torque low speed gear)	
		0	2	2	Increase of steel ratio in the pre-cast concrete, use high strength concrete, identify different type of rings	
		2	0	0	Installation of a yielding support (for example, sliding ribs, openings in the shotcrete, closed or not closed with compressive elements)	
		0	2	2	Improvement of the annular void filling method to stabilize the ring as early as possible.	
		0	3	3	Deformable annular filling in extreme squeezing conditions (the low stiffness)	

Table 16 (*Continued*)

Sl No.	Hazards	Difficulty Level to Implement			Example of Mitigation Measures	
(1)	(2)	(3)			(4)	
		Open	**Single Shield**	**Double Shield**	0	Not concerned
					1	Easy to implement on site, to be previously considered in the design
					2	Medium difficulty of implementation
					3	Exceedingly difficult to implement
iv)	Extremely high water inflow	1	1	1	Advance exploration with sub-horizontal probe drilling with registration of parameters and geophysics	
		2	2	2	Reduction of the permeability by grouting ahead of the machine	
		0	2	0	Closed mode operation in the case of using a Single Shield Multimode TBM, and water pressure up to 15 bar	
		1	1	1	Installation of a muck chute closure gate	
		3	3	3	Reduction of the permeability by freezing (in advance)	
v)	High water pressure	2	3	3	Advance exploration with sub-horizontal probe drilling with registration of parameters and geophysics	
		2	3	3	Long advance drainage of length, at least 2 times tunnel diameter long, in the periphery and/or front ssface of the machine	
		2	3	3	Improve the ground characteristic by grouting ahead of/and around the machine	
		0	2	0	Closed mode operation in the case of using a Single Shield Multimode TBM, and water pressure up to 15 bar	
		3	3	3	Reduction of the permeability by freezing (in advance)	
		0	3	3	Improve the ground characteristic by grouting around the segmental lining	
		2	3	3	Drainage boreholes around the lining	
vi)	Mud inrush	1	1	1	Treatment of the extracted ground by foams (to manage mucking-out difficulties)	
		2	2	2	Clean TBM area with pumps, excavator etc. in the front zone of the machine.	
vii)	Face instability	1	1	1	Advance exploration with sub-horizontal probe drilling with registration of parameters and geophysics	
		2	2	2	Improve the ground characteristic by grouting ahead of/and around the machine	
		0	2	0	Closed mode operation in the case of using a Single Shield Multimode TBM, and water pressure up to 15 bar	
		2	2	2	Advance drainage boreholes to release the water pressure	
		1	1	1	Moderate driving – Reduction of rotation speed and penetration	
		1	1	1	Appropriate design of cutter head – Wedges to protect discs; high-resistance wear plates; high-resistance disc cutters (450-550 mm); many small bucket openings; closable manholes	
		1	1	1	Appropriate torque reserve (high torque low speed gear)	
viii)	High temperature	1	1	1	Appropriate design of ventilation (increase of airflow)	
		2	2	2	Foresee systematic equipment of chilled water pipe system in the tunnel and the TBM	
		2	2	2	Catch water as soon as possible with advance drainage boreholes to avoid heat transfer to the air.	
		1	1	1	Reduce shift time for workers	
		1	1	1	Use of additive/formula to delay the grout hardening	

ANNEX E

(*Foreword*)

COMMITTEE COMPOSITION

Rock Mechanics Sectional Committee, CED 48

Organization	*Representative(s)*
Indian Institute of Technology Roorkee, Roorkee	DR N. K. SAMADHIYA **(*Chairperson*)**
AIMIL Limited, New Delhi	SHRI AKHIL RAJ
Amberg Technologies, Gurugram	SHRI KRIPAL CHOUDHARY SHRI RAKESH PANDITA (*Alternate*)
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