Guidelines for selection of tunnels and tunneling methods

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Abstract

Tunnels are long underground openings excavated to create space through existing mountains, roadways and water bodies for a large number of purposes such as water conductor systems, water supply systems, irrigation schemes, underground roads and railway lines. This paper discusses various factors such as geological features, ground water regime, ground cover, underground utilities, presence of sensitive surface facilities, construction risks etc. Various factors responsible for deciding upon the shape, size, portal locations, support measures etc are also discussed. Assessment for the requirement of tunnel lining and grouting procedure are very important during tunnel designing and construction.

1.0 Introduction:

Tunnels can be broadly defined as long underground openings, excavated for different purposes. They are generally constructed to traverse through physical barriers such as mountains, existing roadways, existing railways, existing water bodies etc. Tunnels are mostly constructed as water conductor system and for diverting river water during construction stages in Hydro Power Projects and as pathways for roads and railways to cross mountains. Tunnels are also used in underground road and railway schemes. Tunnels are excavated through different types of materials like rocks of different strengths/classes, soft soils, difficult ground etc. by adopting appropriate equipments/ methodology. Planning for a tunnel requires multi-disciplinary involvement and assessments, and should satisfy the functional requirements during operation stage also, in addition to the structural and safety aspects during execution. For road tunnels and railway tunnels, generally the same operating standards as for surface roads/railways shall apply. Certain additional considerations, such as lighting, ventilation, life safety, operation and maintenance, etc should be addressed specifically for road and railway tunnels. For water conveying tunnels, in addition to structural aspects, hydraulic aspects like, head losses, turbulence etc. also shall be taken care of. The main aspects to be considered in the design of tunnels are the alignment, geometry (shape and size of opening), optimum tunneling method and supporting system. All these factors depend upon the type of materials encountered along the tunnel alignment and their geological and geotechnical parameters, as well as site constraints if any. In order to obtain information regarding the type of materials, geological and geotechnical aspects, detailed investigations and topographical surveys will have to be carried out. In this paper, the authors have tried to present a broad overview of the planning aspects of tunnels and tunneling methods, based on their professional experience, mainly in the field of hydro electric power projects and also based on available literature on the internet.

2.0 Geometry and Alignment of Tunnels:

2.1 Alignment:

The layout is usually governed by the geological features of the surrounding hills. Complicated geological conditions and extraordinary geological occurrences such as intra-thrust zones, very wide shear zones, geothermal zones of high temperature, cold/hot water springs, water charged rock masses, intrusions, fault planes, etc. should preferably be avoided. Sound, homogeneous isotropic and solid rock formations are the most suitable for tunneling work. However, in some regions like the Himalayan region, such conditions are rather rare compared to the hills of peninsular India. Hence, geological investigations have to be carried out in detail before a tunnel alignment is finalized.

Geotechnical issues such as the soil or rock properties, the ground water regime, the ground cover over and on sides of the tunnel, presence of underground utilities and obstructions such as boulders or buried objects, and the presence of sensitive surface facilities should be taken into consideration while evaluating tunnel alignment.

The selection of a tunnel alignment should also take into consideration site specific constraints such as the presence of contaminated materials, special existing buildings and surface facilities, existing utilities, or the presence of sensitive installations such as historical landmarks, educational institutions, cemeteries, or houses of worship. In addition to structural requirements, inundation of the tunnel by floods, surges, tides and waves, or combinations thereof resulting from storms must be considered while fixing the alignment of tunnels.

2.2 Shape:

The shape of the tunnel will mainly depend upon the method of excavation adopted, the ground conditions and the space requirements from operation point of view in the purpose for which the tunnel is planned. In general, the following shapes are provided for tunnels:

a) **Circular section**: The circular section is most suitable from structural and hydraulic considerations. However, it is difficult for excavation, particularly where cross-sectional area is small. For tunnels which are likely to resist heavy inward or outward radial pressures, it is desirable to adopt a circular section. In case where the tunnel is subjected to high internal pressure, but does not have good quality of rock and/or adequate rock cover around it, circular section is considered to be the most suitable. Apart from structural requirements, circular shape will have to be invariably adopted where the excavation is carried out through mechanical boring (such as by using TBM, road header etc.)

b) **D-section:** This type of section would be found suitable in tunnels located in massive igneous, hard, compacted, metamorphic and good quality sedimentary rocks where the external pressures due to water or unsound strata upon the lining is slight and also where the lining is not required to be designed against internal pressure. The principal advantages of this section over horse-shoe section (discussed in next paragraph) are the added width of the invert which gives more working floor space in the heading during driving and the flatter invert which helps to eliminate the tendency of wet concrete to slump and draw away from the tunnel sides after it has been cast.

c) **Horse-shoe section:** These sections are a compromise between circular and D sections. These sections are strong in their resistance to external pressures. Quality of rock and adequate rock cover in terms of the internal pressure to which the tunnel is subjected govern the use of these sections. Modified horse-shoe section offers the advantage of flat base for constructional ease and change over to circular section with minimum extra cost, if required at weak stretches.

d) **Rectangular section**: This section is generally used for shallow road/railway tunnels, where mostly cut and cover method is adopted for tunnel construction.

2.3 Size:

The size of tunnel is generally fixed, considering the operation requirements of the purpose for which the tunnel is planned. However, from construction point of view, a minimum size is to be provided, depending upon the machinery used for excavation, mucking arrangements planned and ventilation arrangements.

3.0 Structural Aspects:

3.1 Tunnel portals:

It is essential to design the entry and exit points of the tunnel very carefully. The portals are built of structural steel and concrete to safely absorb the shock of any potential avalanche, from the hill slopes. In the case of road/railway tunnels, the portal buildings can also house portal fans (for tunnel ventilation), emergency vehicles and equipment, power distribution equipment, furnaces to heat ice-control panels within the tunnel and remote operations controls. However, in the case of tunnels conveying water, the portals are constructed in the form of an arch. Since at these points the water enters or leaves the tunnel, they are prone to hydraulic head loss and proper transition shape has to be provided to keep the loss minimum and to avoid cavitation.

3.2 Tunnel supports/reinforcement:

Whenever an opening is made by excavation in a medium already in equilibrium, the material around the opening becomes unstable and tends to move. If the surrounding medium is highly jointed, then the loose materials may collapse, thereby increasing the instability further. Hence in order to prevent such failures, appropriate supports/reinforcement is to be provided. The reasons for providing support are manifold.

a) Sometimes support is required for the immediate stability of the opening. It may be furnished even before excavation, for example by air pressure, fore poling or ground improvements. When a shield is used for immediate support, a lining is erected inside the shield, and the annular void cleared by the shove of the shield is at least partly filled with pea-gravel and/or grout.
b) Even where instability or collapse of the opening is not imminent, support may still be required for various reasons, usually to control or limit deformations. Large deformations may lead to undesired settlements of the ground surface or to interference with other structures. In a jointed or weak rock the material above the opening tends to loosen and may sooner or later exert considerable loads on the support. These loads are reduced if loosening is prevented by suitable support.
c) Although the initial stability may be satisfactory, conditions may be such that final equilibrium cannot be reached without support. This may occur in jointed rock mass subject to progressive loosening, in creeping or swelling materials, and in materials whose strength decreases with time.
d) It is impossible and undesirable to avoid deformations in the soft ground altogether. Some movement is necessary to obtain a favorable distribution of loading between the medium and the support system. In each instance, the engineer must determine how much movement is beneficial to the behavior of the tunnel, and at what movements the effects will become detrimental. The engineer's conclusions regarding these matters determine whether and where restraints are to be applied to the tunnel walls. His conclusions also determine the character and magnitude of those restraints. In tunnels in hard rock the beneficial movements take place almost immediately, and subsequent movements are likely to lead to loosening and additional loading. Hence, in this case rapid construction of supports is usually desirable.

Usually provided tunnel supports are ribs and lagging, rock bolts and dowels/micro piles, spiling/fore poles, lattice girders and shotcrete (with or without wire mesh reinforcement).Another new trend is the use of steel fiber reinforced shotcrete. The fiber doesn't change the compressive strength significantly but does produce a significant increase in the toughness or ductility of the shotcrete. Wire mesh or reinforcement mats have proven to successfully arrest and hold local raveling until sufficient shotcrete can be applied to knot the whole system together and hold it until the shotcrete attains its strength.

3.3 Lining:

Road tunnels are often lined with concrete and finished, except where very competent rock is present. Shotcrete can also be used as a final lining. It is typically placed in layers with or without welded wire fabric and/or with steel fibers as reinforcement. Precast segmental lining is primarily used in conjunction with a TBM in soft ground and sometimes in rock.

Road tunnels are often finished with interior finishes for safety and maintenance requirements. The walls and the ceilings often receive a finish surface while the roadway is often paved with asphalt pavement. The interior finishes, which usually are mounted or adhered to the final lining, consist of ceramic tiles, epoxy coated metal panels, porcelain enameled metal panels, or various coatings. They provide enhanced tunnel lighting and visibility, provide fire protection for the lining, attenuate noise, and provide a surface easy to clean.

For hydraulic tunnels, the lining is a protective layer within the tunnel made of plain or reinforced concrete. Tunnels may be completely lined, partially lined, or even unlined. Tunnels in good sound rock may be kept unlined. However, lining is recommended when:

a) The internal water pressure exerted by water conveyed by the tunnel is high, say above 100m of water head. For very good competent rock, tunnels may be kept unlined for pressures even up to 200m water head.
b) The rock strata through which the tunnel passes has low strength and where the rock is anisotropic.

Lining in tunnels conveying water under free flow conditions may be un-reinforced. The external rock load is expected to be carried by the steel supports. Usually, a tunnel lining has to be reinforced when the depth of rock cover (from the tunnel soffit up to the free surface of the hill) is less than the internal water pressure.

3.4 Grouting:

Grouting is required to fill discontinuities in the rock by a suitable material so as to improve the stability of the tunnel roof or to reduce its permeability or to improve the properties of the rock. Grouting is also necessary to ensure proper contact of rock face of the roof with the lining. In such cases grouting may be done directly between the two surfaces.

4.0 Tunneling Methods:

Tunnels are basically built by any one of the following methods:

- **Cut and cover method:**

  In a cut and cover tunnel, the structure is built inside an excavation and covered over with backfill material when construction of the structure is complete. Cut and cover construction is used when the tunnel profile is shallow and the excavation from the surface is possible, economical, and acceptable. Cut and cover construction is used for underpasses, the approach sections to mined tunnels and for tunnels in flat terrain or where it is advantageous to construct the tunnel at a shallow depth.

- **Drilling and blasting method:**

  The basic approach is to drill a pattern of small holes, load them with explosives, and then detonate those explosives thereby creating an opening in the rock. The blasted and broken rock (muck) is then removed and the rock surface is supported so that the whole process can be repeated as many times as necessary to advance the desired opening in the rock. This method can form any shape required. Drill and blast method will have relatively slower progress compared to mechanical boring. Also this method can result in blast induced damage to the surrounding rock.

- **Mechanical excavation by boring:**

  Tunnel boring machines (TBM) excavate rock mass in a form of rotating and crushing by applying enormous pressure on the face with large thrust forces while rotating and chipping with a number of disc cutters mounted on the machine face (cutter head).TBMs have been known to excavate rocks having compressive strength up to 250 MPa.

  There are three general types of TBMs suitable for rock tunneling including Open Gripper/Main Beam, Closed Gripper/Shield, and Closed Segment Shield. The open gripper/beam type of TBMs is best suited for stable to friable rock with occasional fractured zones and controllable groundwater inflows. The closed shield types of TBMs are suitable for friable to unstable rocks which cannot provide consistent support to the gripper pressure. Note that although these machines are classified as a closed type of machine, they are not pressurized at the face of the machine thus cannot handle high external groundwater pressure or water inflows.

  The TBMs have limitation that the radius of curves in tunnels shall be more than 300m and they can form only circular shaped tunnels. Also highly skilled personnel are required for TBM operation. Though TBMs can be used in any type of rock or soil, different cutter heads will have to be used for different types of materials. Hence if the type of material is considerably varying along the tunnel alignment, the use of TBM is not feasible as frequent change of cutters is not practically feasible.

  The basic cutting tool for a road header is a very large milling head mounted on a boom, which in turn, is mounted on tracks or within a shield. Corners must be cut to the curvature of the milling head, but the rest of the walls, crown and invert can be cut to almost any desired shape. In addition, a single road header can cut variable or odd shapes. Because of their adaptability, availability (a few months order time compared to a year or longer order time for TBMs), and lower cost, road headers also may be a choice for relatively short tunnels, say less than 2 Km in length. On the negative side, road headers are far less efficient on longer drives and in hard rock. Road headers may not be effective in rock with an unconfined compressive strength greater than 140MPa.

- **Sequential excavation method (SEM):**

  The Sequential Excavation Method (SEM), also commonly referred to as the New Austrian Tunneling Method (NATM), is a concept that is based on the understanding of the behavior of the ground as it reacts to the creation of an underground opening. In its classic form, the SEM/NATM attempts to mobilize the self-supporting capability of the ground to an optimum, thus achieving economy in ground support. Building on this idea, practical risk management and safety requirements add to and dictate the required tunnel support. The SEM can be defined as a method where the surrounding rock or soil formations of a tunnel or underground opening are integrated into an overall ring-like support structure and the following principles must be observed.

  The shape of the tunnel cross section is designed to comply with SEM principles, which are to (as effectively as possible) activate the self-supporting arch in the surrounding ground. To accommodate this principle, cross section geometries shall be curvilinear, consisting of compound curves in both arch and invert (if constructed in soft ground like conditions). Any straight walls and sharp edges in the excavation cross section shall be avoided. Thus the geometry of the excavation cross section will enable a smooth flow of stresses in the ground around the opening, minimizing loads acting on the tunnel linings. While adhering to these principles the excavation cross section shall be optimized in size to achieve economy. The layout of the invert will depend on the ground conditions in which the tunnel is constructed. In competent rock formations, the tunnel invert can be flat, whereas in weak rock and soft ground, the invert shall be rounded to facilitate ring closure and stability.

- **Jack pushing method:**

  Jacked box tunneling is a unique tunneling method for constructing shallow rectangular road tunnels beneath critical facilities such as operating railways, major highways and airport runways without disruption of the services provided by those surface facilities or having to relocate them temporarily to accommodate open excavations for cut and cover construction. Originally developed from pipe jacking technology, jacked box tunneling is generally used in soft ground at shallow depths and for relatively short lengths of tunnel, where TBM mining would not be economical or cut-and-cover methods would be too disruptive to overlying surface activities.

- **Tunnelling under Immersed conditions:**

  Immersed tunnels consist of very large pre-cast concrete or concrete-filled steel tunnel elements fabricated in the dry and installed under water. They are usually built to provide road or rail connections. They are fabricated in convenient lengths on shipways, in dry docks, or in improvised floodable basins, sealed with bulkheads at each end, and then floated out. Tunnel elements can and have been towed successfully over great distances. They may require outfitting at a pier close to their final destination. They are then towed to their final location, immersed, lowered into a prepared trench, and joined to previously placed tunnel elements. After additional foundation works have been completed, the trench around the immersed tunnel is backfilled and the water bed reinstated.

- **Tunnelling in soft ground:**

Shield tunneling method with Earth Pressure Balancing Machines or Slurry Face machine is the most favoured method for tunneling in soft grounds. The choice of type of machine will be guided by the ground types and conditions to be encountered.SFM is ideal in loose water bearing granular soils. If the percentage of fines in the soil is more than 20 %, SFM is not desirable. EPBM will perform better where the ground is silty and has a higher percentage of fines.

Soft ground tunnels can be excavated by also sequentially by small drifts and openings following the principles of the Sequential Excavation Method (SEM).However, SEM generally cannot compete with tunneling machines for long running tunnels but often is a viable method for:

- Short tunnels.
- Large openings such as stations.
- Unusual shapes or complex structures such as intersections.
- Enlargements.

- **Tunnelling in difficult ground:**

Some difficult situations are indicated below:

a) Instability:

Instability can arise from: lack of stand-up time, as in non-cohesive sands and gravels (especially below the water table) and weak cohesive soils with high water content or in blocky and seamy rock; adverse orientation of joint and fracture planes; or the effects of water. The major problems with mixed face tunneling can also be ascribed to the potential for instability.

b) Heavy loading:

When a tunnel is driven at depth in relatively weak rock, a range of effects may be encountered, from squeezing through popping to explosive failure of the rock mass. Heavy loading may also result from the effects of tunneling in swelling clays or chemically active materials such as anhydrite. Adverse orientation of weak zones such as joints and shears can also result in heavy loading, but this is usually dealt with as a problem of instability rather than loading. Combinations of parallel and intersecting tunnels are a special case in which loadings have to be evaluated carefully.

c) ***Obstacles and constraints:***

Natural obstacles such as boulder beds in association with running silt and caverns in limestone are just two examples of natural obstacles that demand special consideration when tunneling is contemplated. In urban areas, abandoned foundations and piles present manmade obstructions to straightforward tunneling while support systems for existing buildings and for future developments present constraints which may limit the tunnel builder's options. In urban settings, interference conflicts, public convenience or the constraints imposed by the need or desire for connection to existing facilities will sometimes result in the need to construct shallow tunnels, which have a range of problems from working in confined spaces, avoiding subsidence and uneven ground loading and support.

d) ***Physical conditions:***

In areas affected by relatively recent tectonic activity or by ongoing geothermal activity, both high temperatures and noxious, explosive or deadly gases may be encountered. In an urban setting, contaminated ground may be encountered and will be especially troublesome when found in association with other difficult conditions.

e) ***Mixed face tunneling:***

The term "mixed face" usually refers to a situation in which soil and rock are present on the face of excavation. There will always be water at the interface which will flow into the tunnel once the mixed face condition is exposed. This increases the hazard because of the destabilization of material already having a short stand-up time. Stabilization therefore calls for groundwater control as well as adequate and continuous support of the weak material. Moreover, this support must be provided where energetic methods, such as drill-and-blast excavation, are required to remove the harder material. Dewatering can reduce the head of water, but it cannot remove the groundwater completely; nor can it be realistically expected to offer control on an undulating interface with pockets and channels lower than the general elevations established by borehole exploration. On the whole, consolidation grouting is to be preferred in this situation. It is emphasized that the best time to seal off groundwater is before it has started to flow into the tunnel. Once the water started flowing, it is extremely difficult to stop it from within the tunnel except by establishing a bulkhead.

The choice of the method and equipments under different conditions will depend upon the type and strength of material and the conditions encountered along the alignment of tunnels.

i. In running sand condition, if the ground is permeable, consolidation grouting of the entire sensitive area can be undertaken to stabilize the soil before tunneling.
ii. If the tunnel face is fully sandy or with similarly weak materials, a slurry machine or an earth pressure balanced machine will be required.

iii. Where continuous joints and shears defining large blocks with little or nothing to hold them in place after tunnel excavation are present, initial rock bolting followed by reinforced shotcrete is a reasonable approach.
iv. In general, fault crossings offer the conditions akin to those of mixed face tunneling.
v. If water is running into the tunnel through the working face, a bulk head will be required to stop the flow while the initial grouting is in progress. Grouting into running water is a slow and expensive way to establish a satisfactory grout seal.
vi. One approach to squeezing rock is to go for a simple and workable system of yielding supports.
vii. If ground water is to be totally excluded from the tunnel, the final lining must be designed to carry the full hydrostatic head unless the aquifer is fully sealed off by consolidation grouting.
viii. To tackle high temperature and humid conditions, air may be supplied at a lower temperature, thereby keeping the local conditions bearable, especially if the incoming air is dry enough to accept evaporating moisture.

5.0 Conclusions:

1) Tunnels are long underground openings excavated to create space,
   - To traverse through physical barriers such as mountains, existing road ways, existing railways, existing water bodies etc.
   - For conveying water for various purposes such as water conductor system/diversion tunnels in hydro electric power plants, water supply schemes, irrigation schemes etc.
   - In underground roads and railway lines etc.
2) Tunnels are excavated through different types of materials like rocks (of different strengths/classes), soft soils, difficult ground conditions, under water etc. depending upon the conditions present along the selected alignment of tunnels.
3) The alignment of tunnels will generally be governed by the geological features, ground water regime, ground cover above and on the sides, presence of underground utilities or obstructions if any, presence of sensitive surface facilities, construction risks etc.
4) The shape of tunnel will depend upon the method of excavation adopted, loading conditions, space requirements from functional purpose during construction and operation stages etc.
5) The size of the tunnel will mainly depend upon the space requirements during construction and operation stages.
6) Portals are to be constructed at the inlets and outlets of tunnels, to absorb the shocks from possible avalanches from the hill slopes.
7) Appropriate Supports /reinforcements are to be provided depending upon the type of materials encountered method of excavation etc.
8) Lining may have to be provided depending upon the materials, loading conditions, operation requirements etc.

9) Grouting may have to be resorted to, to control ground water seepage, for consolidation of the surrounding strata, filling up of voids, shrinkage cracks etc. depending upon site conditions.

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In the internet, numerous papers/contributions are available regarding tunnels and tunneling methods, from which the authors have derived information. Though the authors are grateful to all such authors/contributors for providing information, it is not practical to list out all such references. However, the list of some major references is indicated under references. The authors also confirm that the views expressed in this paper are their personal views only and shall not be construed as the views of the organizations where they presently work or worked earlier.

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