Journal of Rock Mechanics and Tunnelling Technology (JRMTT)
26 (1) 2020 pp 27-40

Available online at www.isrmtt.com

Cross Passage Construction Methods for Twin-Tube Tunnel Projects in Urban Areas

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ABSTRACT

Cross passage construction has always been one of the most challenging construction stages of any twin tube tunnel project whether it be railway, highway or MRTS tunnels. The complexities increase manifold in case of urban tunnelling. Various design philosophies and construction methods such as NATM, Top down excavation, Box pushing, bored construction etc. have been adopted worldwide in line with the different ground conditions and the space constraints during cross passage planning. This paper discusses about the challenges, advantages and disadvantages of these cross passage construction methods and their suitability to different ground conditions in India. A summary of the selection of appropriate method for different types of ground has also been provided.

Keywords:Cross passage;Tectonic stresses; Hydraulic fracturing tests; Overcoring; Vertical stress; Horizontal stress; Pressure tunnels; Steel liner.

1. INTRODUCTION

Construction of Cross Passages have been always the most challenging work in twin tubes tunnelling project in which, according to National fire protection association (NFPA) guidelines, cross passages must be constructed at maximum interval of 244m. The challenges become much more extreme when ground consists of very fine silty sand combined with high water table. The biggest challenge in the construction of these cross passages is to limit the surface settlements especially if structures like roads, buildings etc. are lying just above the cross passage.

Many construction methodologies have been devised in the past to overcome these challenges. These different construction methodologies have different level of suitability and constraints. While, some of them are only applicable in hard rock, others might be possible to execute in soft grounds only.

Selecting the right methodology of construction and design depending upon the ground strata is the most important activity for cross passages construction. The methodology should be safe, feasible and economical at the same time. Hence, it is very important to understand these different types of methods and their applicability in different ground conditions and keeping in mind the space constraints. The limitation, advantages and applicability of these methods have been discussed in detail.

2. Sprayed Concrete lining Method

Sprayed concrete lining method is the most common method for Cross passages construction. This method has been adopted for different types of ground including hard rock as well as soft ground with high water table. However, risk of surface as well as ground settlement increases as we move from high strength to low strength ground. This method becomes more complex when soft ground (silty sand / sandy silt) is encountered with high water table. To overcome, such adverse ground conditions, pre-excavation ground treatment/improvement is advised.

2.1 Without Pre-excavation Ground Support and Treatment

This method is generally used when the ground is stiff with moderate to high cohesive values (rock, clay and compacted sand/silt) along with low water table. Typical NATM scheme is generally followed while excavating this type of ground. The ground is excavated for a typical round length ranging from 0.8-2.0m (designed as per ground conditions) and is supported using Shotcrete, Lattice girders and wire mesh as per design. A typical excavation scheme is shown in Figure 1 for the above mentioned grounds.

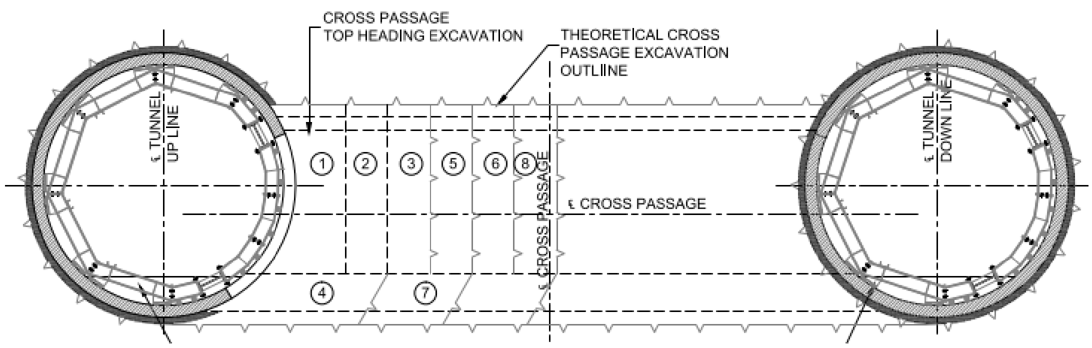


Fig. 1 - Typical excavation scheme

While Soil can be excavated using Jack hammer or excavator depending on the space available, hard rock should be excavated using only control blasting. While excavating hard rock, vibrometers must be used at all time to control the vibrations so as to limit any damage to the Main tunnel segments. Localized grouting, face anchors and forepoling might be required during excavation in this type of scheme depending on the ground behaviour. Rock bolts shall be used in case of rock.

2.2 With Pre-Excavation Ground Support and Treatment

The complexity of sprayed concrete lining method increases manifold when the ground is expected to be weak and the water table is high. In these cases, ground improvement is generally done before excavation of the cross passage as well as before opening the segment of the main tunnel. Many techniques have been developed and implemented in the ground in past some of which have been discussed below:

a) Pipe roofing

Pipe roofing is the technique of pre-reinforcing the ground (generally above the crown of the tunnel) ahead of the tunnel face to ensure that tunnel crown does not fail and hence, to limit the surface settlements. A typical pipe roofing scheme is shown below in Figs. 2 and 3.

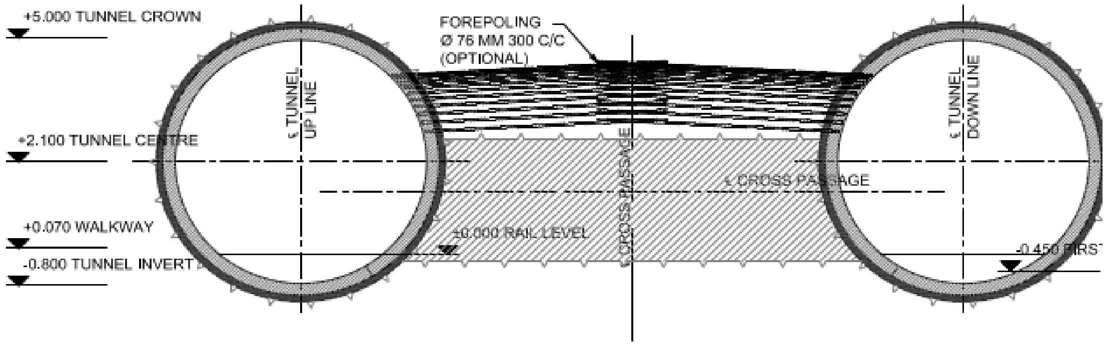


Fig. 2 - Pipe roofing scheme (L-Section)

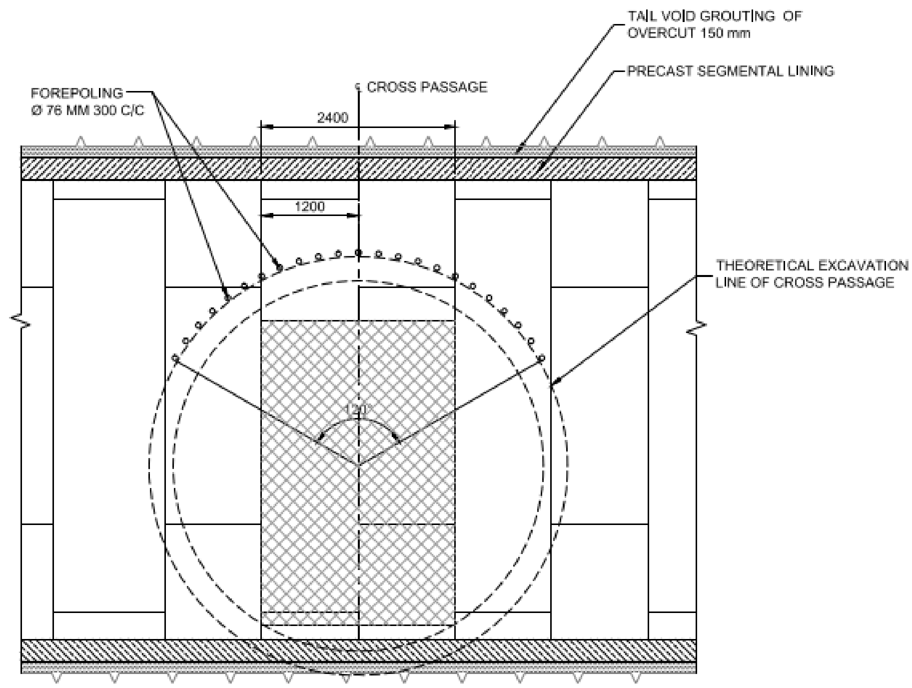


Fig. 3 - Pipe roofing (on the cross passage face)

Forepoling is used in the cases where huge surface and crown settlements are expected as per numerical analysis (Latif et al., 2012). This happens in the low cohesive and low strength ground and sometimes when the overburden above the cross passage is very low. The installation of the support utilizes the area around the crown and sides of the tunnel wall. It acts as a temporary reinforcement to enhance the soil structure before any excavation is done.

b) TAM Grouting

Tube-A-Manchette (TAM) grouting is a very efficient and cost effective grouting technique used generally for foundations, tunnel and mines.

This system is based around the TAM which basically consists of a length of pipe with small holes drilled around the circumference and at equal intervals along the length of the pipe. Each set of holes is covered by a rubber sleeve (or manchette), which allows the whole arrangement to act as a series of one-way valves. That is, flow out through the holes is permitted by expansion of the rubber sleeve but flow in the opposite direction is prevented by the sleeve collapsing onto the pipe. Schematic details of TAM grouting are shown in Fig. 4.

The scheme has been used extensively in the cross passage construction all over the country where water table is above the crown in addition to ground mainly composed of sand and silt. In this ground, excavation becomes much more difficult due to high water ingress which sometimes bring soil with it leading to ground volume loss which can create a huge collapse in terms of cavity formations or surface settlements.

Hence, the grout is injected following above mentioned TAM grouting scheme from both up line and downline tunnels in such a way that the ground becomes close to impermeable around the cross passage excavation line (Fig. 5). This scheme not only reduces water ingress quantity while excavation but also increases the ground strength and its stand-up time.

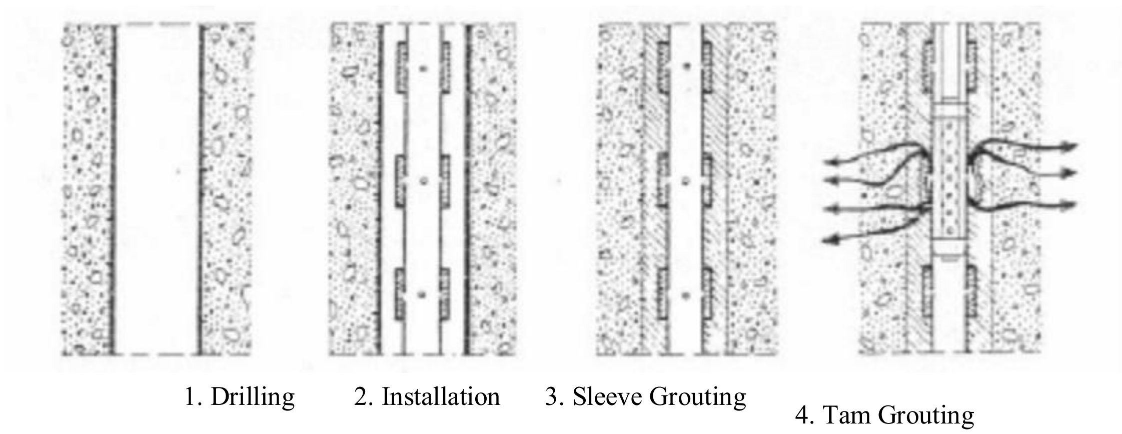


Fig. 4 -TAM grouting schematic (Courtesy: Spargrp.com)

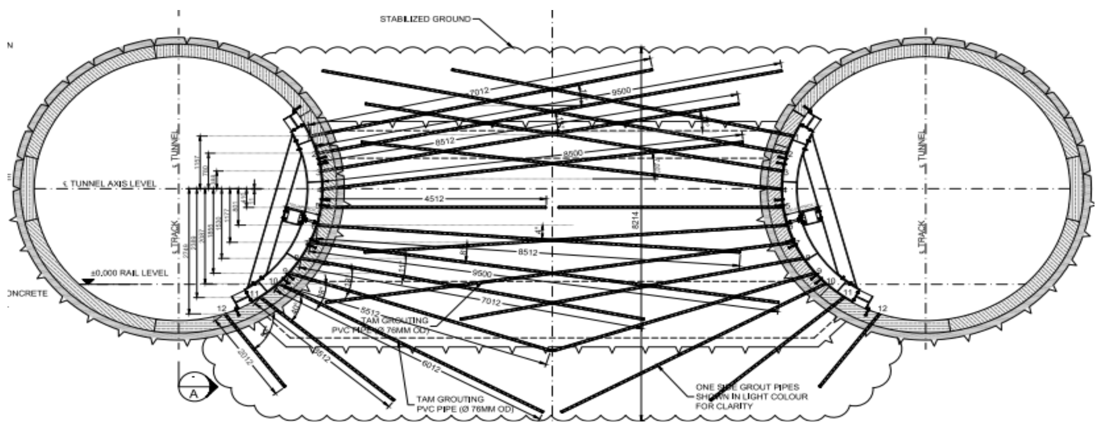


Fig. 5 - TAM grouting in cross passages

c) Jet Grouting

Jet grouting historically has been considered as a risky ground improvement process due to spoil generation and high pressures involved which might damage tunnel segments. But with good experience, site control and proper design the system can be riskless than other processes (Arroyo et al., 2011). This is an effective method of ground improvement if it is planned properly. Jet grouting consists of drilling down with a small diameter rod system, typically 90-130mm in diameter and then injecting high pressure mortar, with or without other accompanying fluids (water, air) (Fig.6). There are three basic systems available:

(a) Single System
(b) Double system
(c) Triple System

The soil-cement mixture sets “in situ”, resulting as a stiffer, stronger, more impermeable and less ductile material than the original soil. The basic reasons for jet-grout success are clear, as of all the means of ground injection, jet is not only the fastest procedure, but is also the only one suitable for multipurpose improvements like strengthening, stiffening and impermeabilization. This method is suitable for all types of sandy strata with high water table. To protect the tunnel segments from being affected by the grout pressure, this ground improvement method can be planned even before the tunnelling operations.

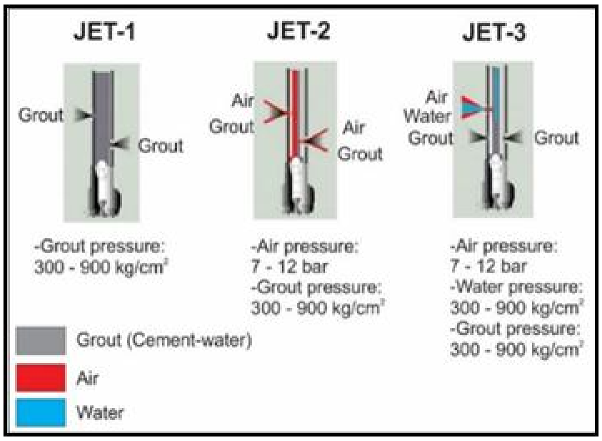


Fig.6 - Types of jet grouting

d) Ground Replacement by Micro-Piling

This method is possible only when there is construction space available on the top of cross passage for Micro-piling (Fig.7). In this method, the ground to be excavated is replaced by low strength grout piles which are then excavated using a breaker through the opening in main tunnel. In this method, the main advantage is saving of support material to be used while excavation.

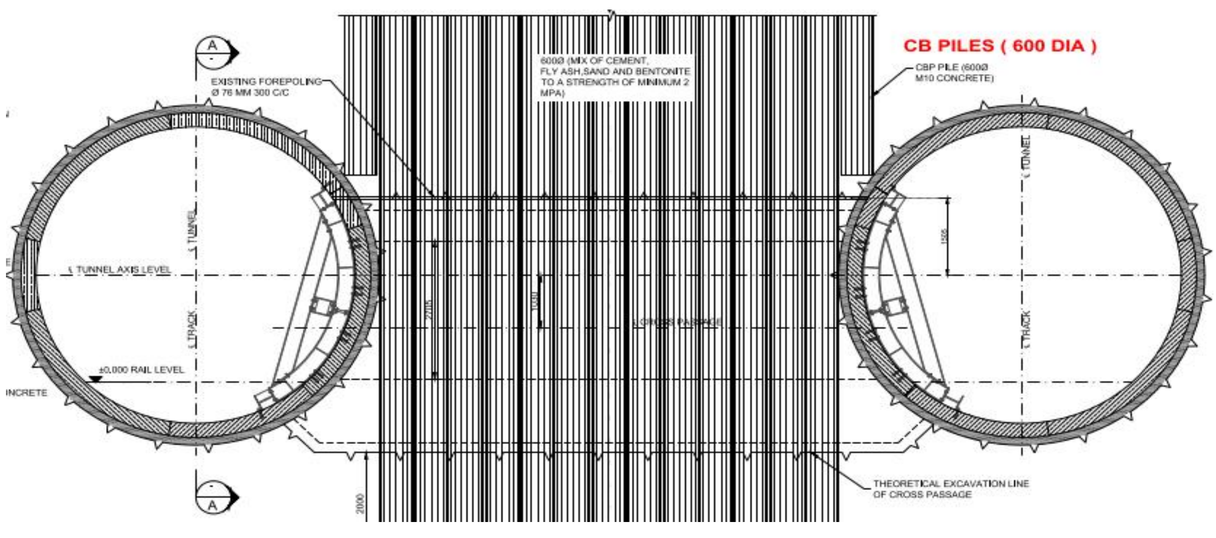


Fig. 7 - Ground replacements for cross passages

This scheme is also effective in the locations where ground is mainly composed of sand and silt along with high water table.

e) Ground Freezing Method

This is one of the most effective ground improvement method in the ground with high water table. In this method, the in-situ water is artificially frozen by a freeze system. This creates a frozen soil mass where the ice (formed) binds the soil particles just like cement in concrete. The resultant soil mass is, thus, both water proof as well as structurally stable.

The freezing can be done both from inside the main tunnel as well as from the ground surface. Chilled calcium chloride brine is pumped through steel freeze pipes with caps welded at the bottom. The refrigeration plant for cross passages can be installed inside the tunnel as well. The whole refrigeration of soil mass takes around 6-10 weeks depending on the environmental and ground conditions (Fig.8). The frozen mass is then excavated and supported with shotcrete. The ground should be kept frozen in this method until the final lining is done and cross passage is completed (David et al., 2015).

This method is expensive as compared to other methods. It makes sense to use this method if many cross passages needs to be constructed.

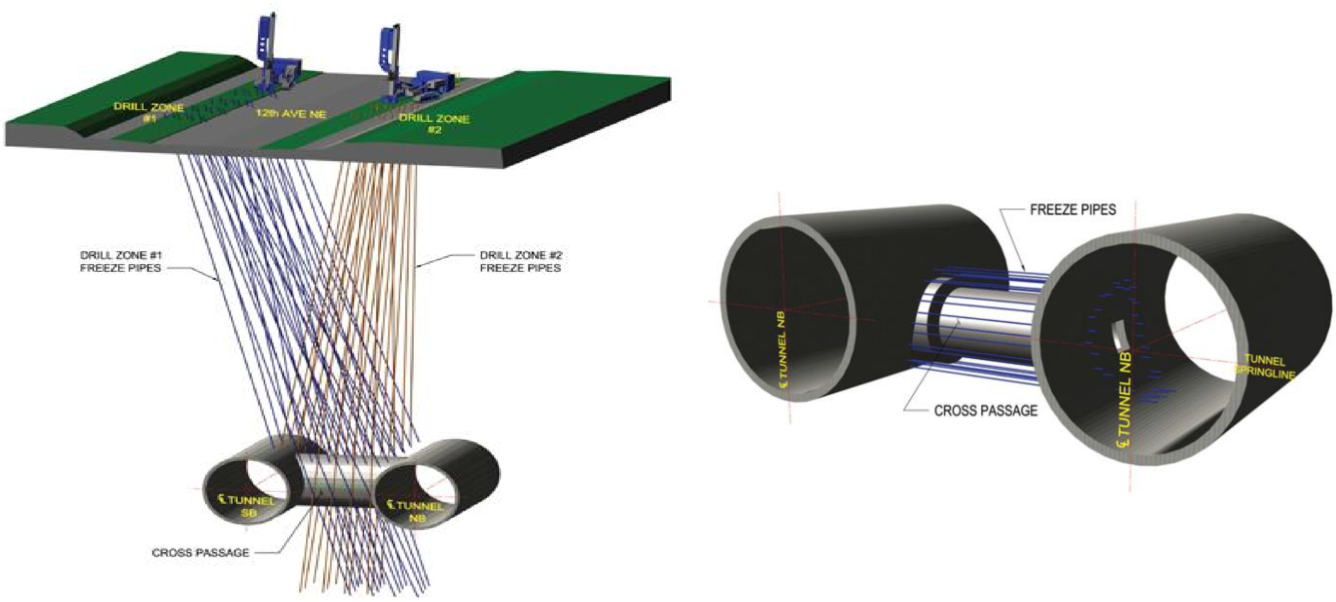


Fig.8 - Typical vertical and horizontal ground freezing scheme (Sopko et al., 2013)

The expertise and machinery, however, for this method is rarely available and hence, never been used in India for cross passages till now.

3. BOX-PUSHING METHOD

This is a recent addition to cross passage construction methods used in Bangalore as well as Delhi Metro. While in Bangalore, steel boxes were pushed into the ground, in Delhi, RCC boxes of pre-defined dimensions were pushed using jacking arrangement taking thrust from the main tunnel (Casasus and Bansal, 2017). The general arrangement of RCC boxes and the cross section is shown in Figs. 9 and 10 respectively. This method again is successful and economical only in ground where high water ingress mixed with soil is expected.

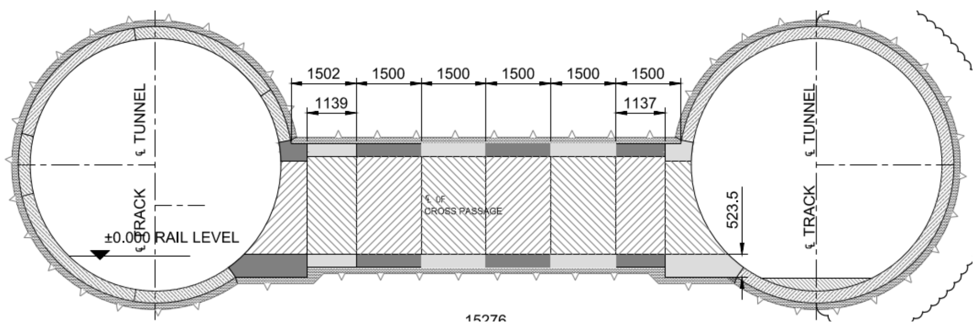


Fig.9 - General arrangements of RCC boxes

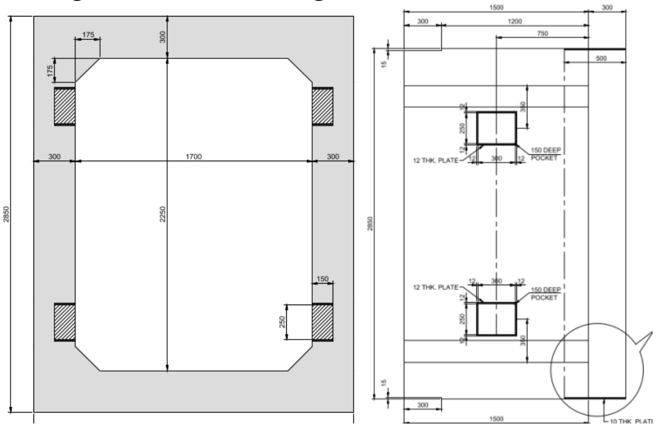


Fig.10 - Cross section and longitudinal section of RCC box

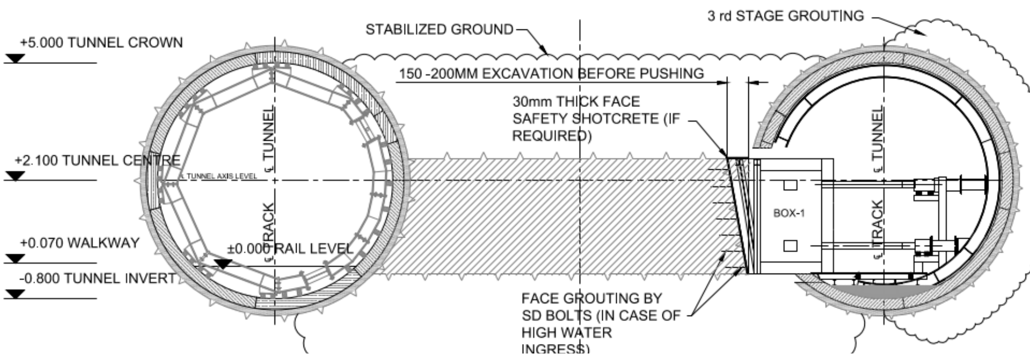


Fig. 11 - Excavation scheme of cross passage

The boxes are pushed into the ground at a stroke length of 100-150mm. The cycle of excavation is - first to excavate up to 100-150mm and then push the box by same distance to support the excavated portion. It is strongly advised against pushing the boxes through the ground without excavating since the reaction frame is not designed to take those huge forces which might damage the main tunnel otherwise.

The benefits of the scheme turned out to be manifold. The settlement values observed at the ground surface as well as the crown were negligible. The process of excavation was much faster as compared to the conventional method. The safety of the workers was ensured since all the sides (except face) of the cross passage were surrounded by RCC lining of the box and at no time were unsupported.

For the space and design considerations, both RCC and steel box pushing methods face similar kind of problems. Jacking force required for steel sections are lesser for similar sections as compared to RCC and hence, leads to faster excavation. However, during execution, RCC box pushing provides the edge of saving the time of in-situ final concrete lining.

It is observed that waterproofing and joint sealing is much more difficult in RCC box pushing if alignment hasnot been controlled during the pushing. This problem doesnot occur in steel box pushing since even if there is a misalignment, the final in-situ concrete lining will be able to accommodate the waterproofing either by the membrane or by the crystalline grout admixture concrete. Moreover, the in-situ final lining gives the passage a proper shape throughout the alignment.

4. TOP DOWN EXCAVATION METHOD

This is one of the oldest and widely adapted methods used for construction of shallow tunnels, as it is quick and cost effective but its application for construction of cross passages depends upon a lot of factors like type of strata, time of construction, water table, space availability on surface etc. When the cover depth of cross passage is less and the surrounding areas are available for constructing the shaft, this method is considered. Figure 12 below shows a typical scheme of top down cross passage construction method

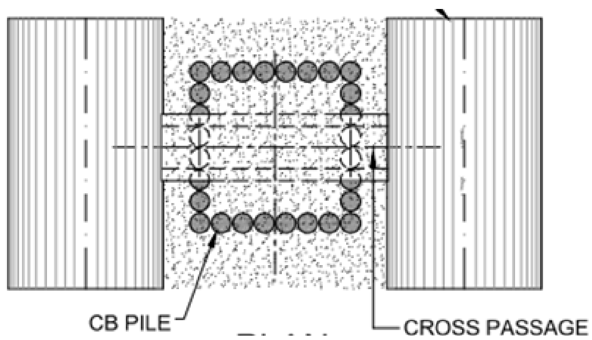


Fig.12 - Typical plan of a top down excavation method

Cut-and-cover method for cross passage excavation is to be done in following basic steps:

- First step is to install temporary supports like CB piles up to the full depth of excavation as shown in Fig. 13.

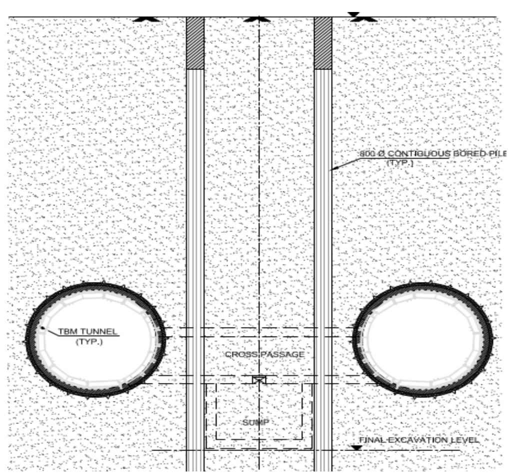


Fig. 13 - Excavation sequence for construction of cut and cover cross passage

- After installation of CB piles the excavation is further carried out to the required depth in small steps and each excavation step is preceded by installation of strut at that level. Once the strut is installed at a particular level the excavation can be proceeded for next 2-3 m of depth depending upon the soil type(Fig. 14)

- Once the excavation reaches the cross passage level, blind struts are installed, CB Pile walls are cut at that level and tunnel segments are opened. Primary lining installation is done in the cross passage (Fig. 15).
- Finally the base slab and walls of the cross passage are casted,soil is backfilled to the top (Fig. 16).

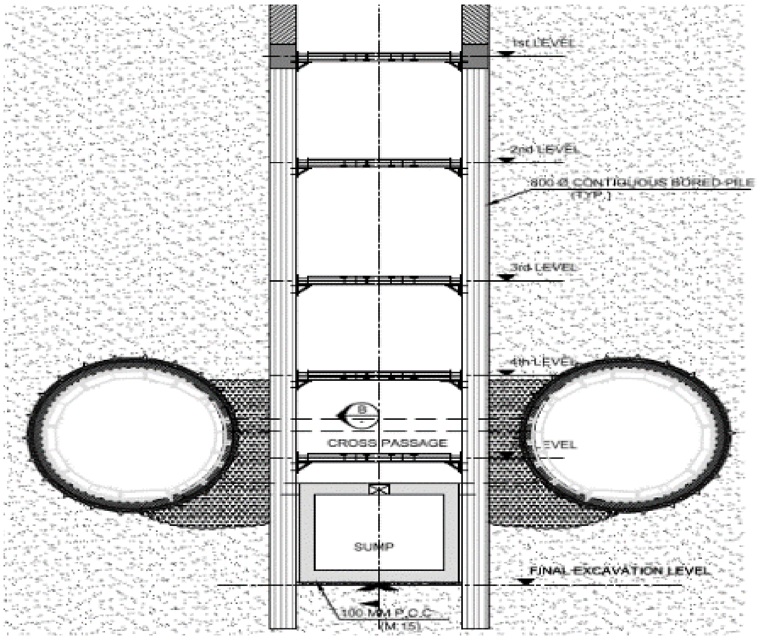


Fig. 14 - Installation of struts for excavation

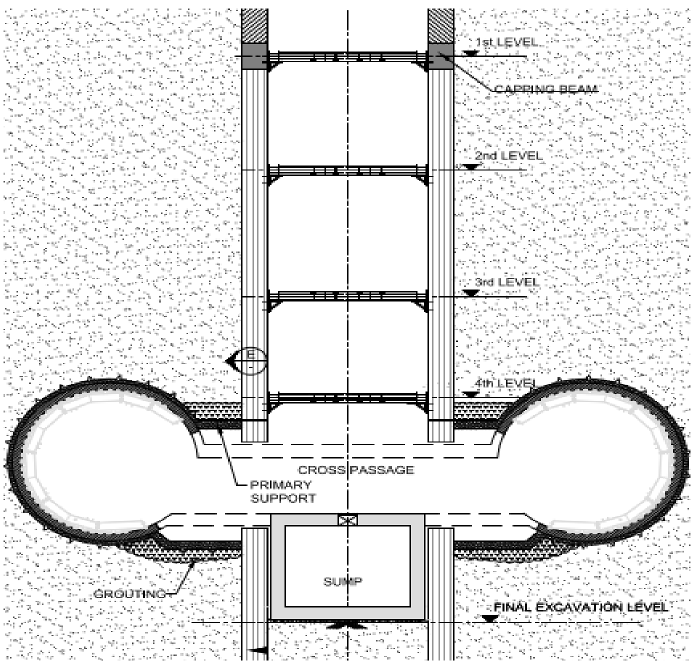


Fig. 15 -Cutting of CB pile at CP level

This method is suitable for all classes of soil and has low cost in comparison to all other methods, as the cost of construction mainly depends on the cost of the nominal supporting systems. The biggest advantage of this method is that the influence to the main body of the tunnel is minimum .The tunnel can be handed over for the track laying and other activities and cross passage construction can be carried out as a parallel activity. Moreover, the requirement of construction technique requires lesser expertise as compared to other methods, and the construction pace is faster.

But it is not preferred in congested areas as the construction causes major disruption at surface because of relocation of utilities already in place, also when there is high groundwater table a heavy construction will be required to resist buoyancy and a proper waterproofing scheme will be required to make the cross passage water tight

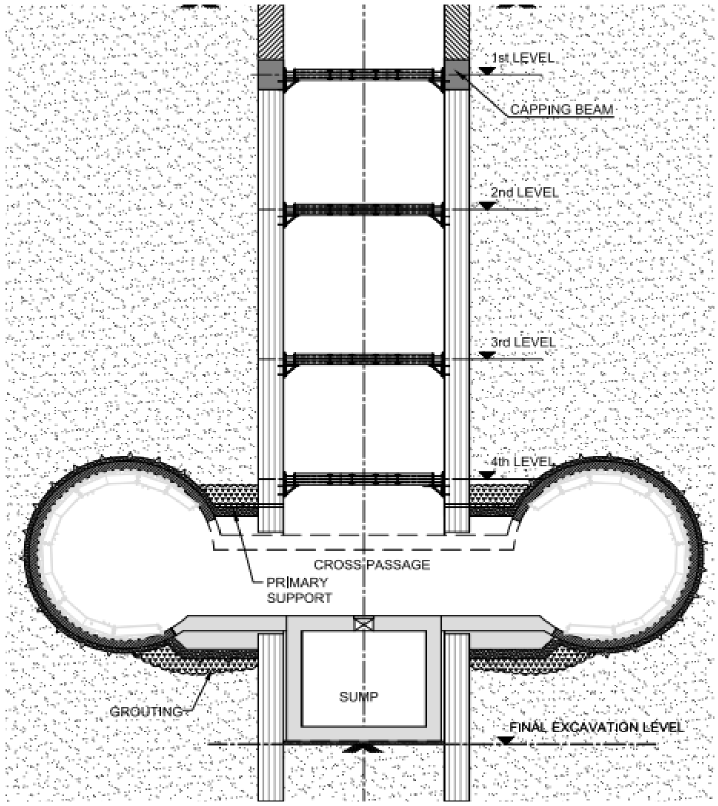


Fig. 16 - Casting of base slab and CP walls

5. MINING WITH SMALL SCALE TBM

TBM mined cross passages are emerging as an innovative solution to execute cross passages in complex geotechnical conditions, keeping in view worker and structure safety, and cost and time schedules. It is a fast way of constructing cross passages and can be cost effective if the numbers of cross passages are more as it promises high production performance for sequential excavation of multiple cross-passages, fast equipment positioning, installation and re-installation along main tunnels, self-contained equipment (external supply piping system not required). This method can be adopted without any pre excavation support system or any kind of ground improvement method.

Asthis is still a new method of construction, it will take some time to master, but it is foreseen that this method can develop into a production-line process, in which the needed equipment and crew can just move along the tunnel, drilling one cross passage after the other, to solve one of the most critical problems in tunnel construction.

Small scale TBM’s are used for excavating the cross passage, these TBM’s use the rail tracks installed to service the TBM excavation of the main tunnel tubes. Cross passage TBM is mounted on the tracks, positioned sideways so that it can drill through the tunnel wall, and then excavate the cross-passage to the parallel tunnel (Figs. 17 to 19).

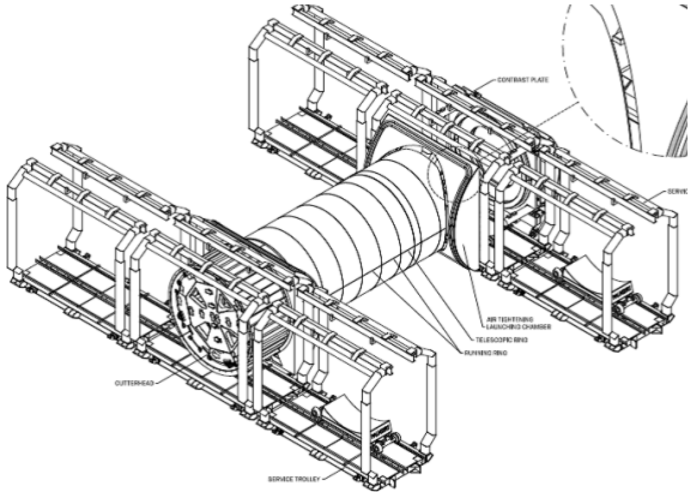


Fig. 17 - Isometric view of small scale secondary TBM (Courtesy: SWS Global Engineering, 2016)

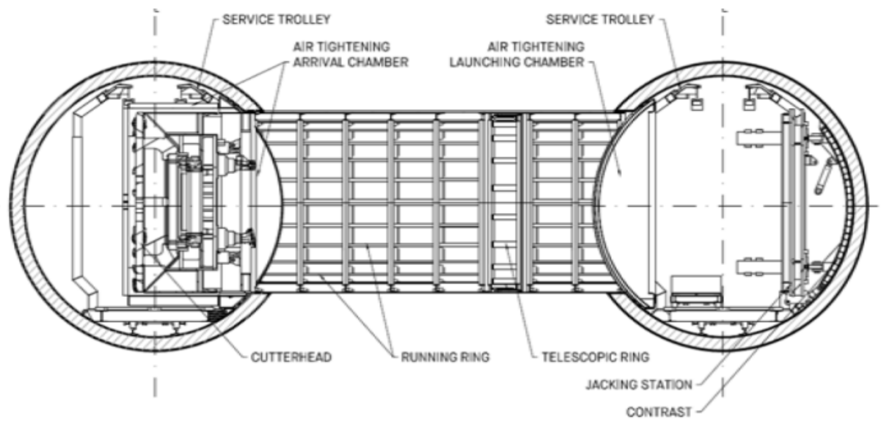


Fig.18 - Typical arrangement for cross passage excavation through TBM

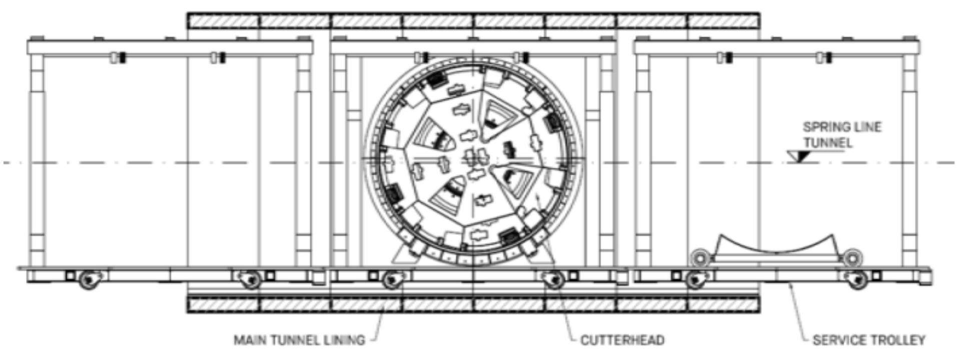
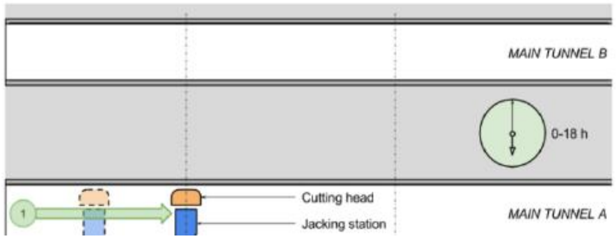
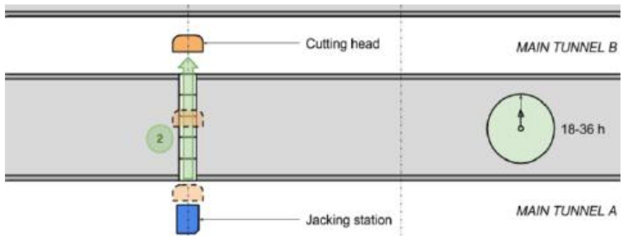


Fig. 19 - General features of cutter head (Courtesy: SWS Global Engineering, 2016)

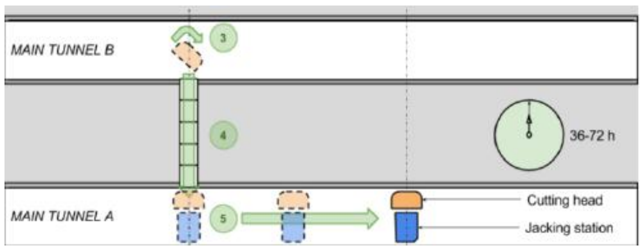
Segmental lining of steel or concrete fitted with sealing gaskets are installed during excavation. No subsequent waterproofing or inner lining is required. The cross passage TBM is then disassembled and pulled back through the new cross-passage to be re-assembled and moved along the tracks to repeat the process for the next cross passage (Fig.20).



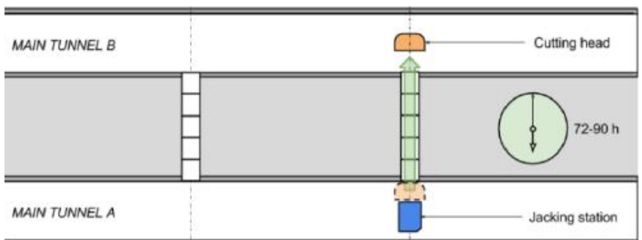
Stage 1: Positioning of jacking station and cutting head.



Stage 2:Exacavation and construction of first cross passage



Stage 3: Cutting head retrieval and reassembly



Stage 4: Excavation of second cross passage

Fig.20 - Sequential arrangement of cross passage TBMs

During TBM operations for construction of the two main tunnels the information about the ground are revealed to a major extent. All this information helps in planning the use the smaller secondary TBM to excavate and construct the cross passages. It also helps in designing their cutter head configuration. The secondary TBM's must be compact enough to fit sideways into the existing tunnel, keeping a margin for giving some access to and from the face. It should be easy to disassemble for its retrieval through the newly built cross passage.

Excavation rate is expected to be higher for this method. As per the available literature, on an average 72 hours are required for propping, boring, installation of the liner, sealing the gaps, completing the junction between the lining segments to the lining of the main tunnels, and retrieval of the TBM unit from the completed cross passage.

TBM mined cross passages are particularly good for challenging deep underground constructions conditions because it can operate in all rock and/or soil conditions, operate under high water table, and in presence of gases also. It is suitable for challenging surface conditions as well. Many city centers have old historic buildings that are vulnerable to subsidence of the surface. Using TBMs for the cross passages minimizes risk to these and other surface structures.

6. SUMMARY AND CONCLUSIONS

Many methods have been discussed above for cross passage constructions. On the basis of authors' understanding and experiencesthe summary of these methods has been provided in Table 1.

The selection of right method for different conditions is the most important aspect of the planning of the cross passage (CP) construction. Despite all the considerations, safety shall be of paramount importance while deciding the methodology. Before deciding any methodology, a complete risk assessment and safe system of works should be devised accordingly and maintained at all times. RA & SSOW should be devised by experienced people and with complete data.

Table 1 - Summary of various methods used for construction of cross passage

Method	Ground Suitability	Land Requirement at Surface	Cost	Construction Time	Remarks
NATM without ground improvement	All types of soils and rock with high cohesion and low water table	NIL	Low	Less	Rock excavation should be done via controlled blasting
NATM with pipe roofing	Ground with low cohesion, fractured rock, shallow cross passages	NIL	Moderate	Moderate	-
NATM with TAM grouting	Silty sand with high water table	NIL	High	High	Grout material should be chosen depending on the ground permeability
NATM with jet grouting	Silty sand with high water table	Required temporarily	High	Less	High skill, precision and continuous monitoring required
NATM with ground replacement	Low strength ground with high water table	Required temporarily	High	Moderate	-
NATM with ground freezing method	Low strength ground composing silt, sand, gravels etc. with high water table	NIL	High	High	Cost per cross passage shall decrease with the increase in number of cross passages
Box –pushing method	Low strength ground with high water table	NIL	Moderate	Moderate	Face stability shall be ensured at all time while excavation
Top-down Excavation method	Shallow cross passages in all types of soil	Required temporarily	Moderate	Moderate	-
TBM Mined	All types of ground	NIL	High	Low	Cost per cross passage shall decrease with the increase in number of cross passages

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