Bifurcating and Widening Tunnels in Urban Environments

P. Yiouta-Mitra¹, K. Kaliakakis¹, P.V. Nomikos¹, A.I. Sofianos¹

¹National Technical University, School of Mining and Metallurgy, Section of Mining, Tunnelling Laboratory, Greece.

ABSTRACT

Underground construction particularities in urban environments often arise under specific project requirements. This study examines the case of bifurcating and gradually broadening tunnel sections in unstable and poor ground conditions as well as the construction techniques to meet them. In the case of a bifurcating tunnel section, the circumstances under which it may be required, the sequence of excavation as well as the difficulties pertaining to the construction are presented. Techniques to overcome possible delays and ameliorate the support system are discussed. A similar yet distinctly different issue is that of a gradually broadening section. The arising needs for heavier support due to the expanding plastic zone around the enlarged excavation are analyzed and support measures and correct implementation, equipment and personnel requirements are discussed. Conclusively, some characteristic actual cases of such construction issues are included.

1. INTRODUCTION

Tunnelling in urban environment is a worldwide well established practice. It ameliorates the quality of life in congested cities by the realization of underground mass rapid transport systems. Consequently, many cities are tackling their urban congestion problems by utilising underground space and developing or expanding underground roads, railways or metros. Constructing road or track bifurcations is a common construction requirement often related to urban environments and generally caused by the need to join two or more different-sized tunnels. However, when the geological conditions are poor, it can be the source of complications and special measures. Poor ground conditions may include among else clayey-silty environments, strata with great variations in composition and degree of weathering and alteration of the deposits, tectonically disturbed rock masses and the presence of water.

2. BIFURCATING SECTIONS

2.1 General description

The issue considered is the bifurcation of a tunnel as depicted in Fig.1a. This need may arise e.g. in the case of a rail when the main rail line needs to be connected to the depot, thus requiring the connection of a triple-track tunnel to a double and a single track.

A special technique need be applied in order to achieve this connection. As it is not possible to pass from a smaller diameter to a larger one in a linear and continuous fashion due to the risks involved, the two tunnels are separately constructed up to a point and a bifurcation chamber is then excavated. Indicative dimensions can be seen in Fig.1.

The construction of the bifurcation section may be achieved with the NATM method, with the standard phases of excavation and temporary support and most importantly, continuous monitoring.
2.2 Construction of the bifurcation

An intermediate tunnel taking up space from both tunnels is first excavated. It starts at the single track tunnel, heads obliquely towards the double track and then extends parallel to the latter as far as required to meet the transition boundary, as depicted in Figure 1b. The excavation can be performed by use of a crawler excavator with hydraulic hammer mounting capabilities while tunnel advance exceeding 1 m is not advisable.

The process can be quite difficult since there is not enough room for the excavator and the loader to work simultaneously at the tunnel face. The excavator is in that case required to back out of the tunnel to make room for the loader that will remove the material from the working face. This manoeuvring may take place as often as thrice during a work cycle causing great inconvenience and delay. The shotcrete unit is similarly obstructed from reaching the face in case of an emergency e.g. an unstable wedge or a collapsing roof. Such emergencies can be completely avoided by spiling the roof and stabilising the face with fibreglass rockbolts. Space insufficiency problems could be solved when smaller equipment is used for the construction of the intermediate tunnel. Nevertheless, it is not uncommon for contractors to continue with the same large equipment used for the entire project, in order to retain a certain routine in the handling of equipment and be spared the time of adaptation of the workers to the smaller machines.

Support measures for the intermediate tunnel include steel ribs positioned according to the excavation advance of 1 m. The oblique part of the intermediate tunnel results in a radial layout close to the point of direction change. The installation is typically performed. An important issue with this support is to obtain maximum contact with the surrounding ground so that the desired rigidity of the system is obtained. If the steel ribs are very thick, then it is possible that the shotcrete will not quite fill the space between rib and arch, thus causing innate instability of the support. It may well be better to use lighter steelsets at shorter distances while maintaining the thickness of the shotcrete.

The last shotcrete lining is applied at some distance from the excavation and can be reinforced with wire mesh. At the same distance the invert is completed, embedding the steelsets’ footings in concrete. After the completion of the intermediate tunnel, it is time for the actual bifurcation into two tunnels to be constructed (Fig. 2). Since the intermediate tunnel covers an area that will be occupied both by the single and the double-track tunnels, the respective support measures need be installed for each tunnel. Part of the steel ribs and shotcrete of the final tunnels are installed in the intermediate tunnel, a procedure requiring great care as to correct positioning and perfect stability. As the two tunnels are closing in on each other at the transition point, the installation starts there and proceeds backwards so that there is ample space for the workmen and the equipment. The ribs are welded onto short bolts in the ground and the roof. A steel plate is also welded at the top of the rib to provide the means of
connecting it later to the rest of the rib. Some scaffolding may be needed but is afterwards removed. Finally, the space between the steel sets is filled with concrete.

Fig. 2. Constructing the bifurcation: Cross-section and plan view of intermediate tunnel.

The rest of the construction of the two tunnels presents no surprises other than having part of the support already in place. Since the ground conditions are poor, the support measures would easily include rockbolting, shotcrete with wire mesh or fibres, the aforementioned steel sets, drainage as required and invert. Also, the excavation of the double-track tunnel would be performed in two stages. That means that, depending on its elevation with respect to the single tunnel, either the first or the second phase support will have been installed; not both. When in the vicinity of the transition point, spiling the roof with adequate for the transition look out angle and installation of fibreglass bolts at the face is a good precaution against collapses.

The actual transition from two tunnels to one is performed in two stages: Construction of part of the triple section through the single and then construction of the rest of the section or vice versa.

3. WIDENING SECTIONS

The need for a gradually widening tunnel section may occur in the case of a road tunnel meeting an interchange or when an underground rail line reaches a station.

The transition would typically take place within 20-30 m when passing from a double to a triple track, with a gradual widening of the section until the desired cross-section is achieved. A larger number of support measures are required in order to ensure the desired stability. Prior to the excavation spiling, forepoling and rockbolting of the face would be applicable while temporary support could include micro piles, steel ribs, rockbolts, shotcrete, invert and a drainage system. The sequence of excavation and support more analytically will be presented.

Spiles are the means for a first safe enlargement of the section. This first enlargement will provide the necessary space for the heavier forepoling equipment that will follow. The spiles are installed in such a way as to gradually widen the tunnel section. The length of application depends on the look out angle but a portion of 1/6 of the total length for the widening is usually enough. The drilling vehicle should be chosen according to such advantages as feed roll over to drill upwards when below its horizontal axis, water drilling to avoid dust, suitable capabilities in length of drilling, percussion pressure and impact power and finally decide whether movement on crawlers is required by the state of the tunnel floor.

Forepoling follows and can be carried out in one or two phases, depending on the situation. If the ground conditions are extremely poor or the forepoles to be installed more than twenty, then it would be more economical and less time consuming to install them simultaneously with drilling. Otherwise, when the drilling is completed, the tubes are manually inserted. Although the latter takes up double the time, it is nevertheless more economical from the point of view of the personnel required.
The pipe forepoles are inclined upwards so grouting is achieved by use of two PVC tubes of unequal length and able to withstand high pressure e.g. 9 bars. The cement enters through the shorter rubber tube and fills the perforated steel tube and the space between it and the surrounding rock until it reaches the other end of the hole. There, it encounters and flows into the longer rubber tube that had acted as an air exit up to that point. Correct pressure inside the hole is of course very important and should be checked.

When the tunnel face is collapsing, grouting fiberglass dowels may be necessary in order to obtain stable conditions. These have the advantage of being lightweight and very strong and they are also easily cut and disposed of as the face advances. However, drilling can be quite devious since poor ground, presence of water and even alterations in the ground after some meters cause collapses inside the hole. Even if the blockage is successfully dealt with, it is still possible that the collapse has not stopped and that the bolt cannot be installed unless the hole is drilled again. The situation can become extremely time-consuming.

Fig. 3. Indicative support design of gradual widening section.

The excavation is carried out in at least 2 phases for the top heading due to the large dimensions and the poor ground. However, the spaciousness makes work easier. It is not uncommon to excavate and muck simultaneously. Temporary support includes shotcrete, rockbolts, steel ribs and of course drainage. It is interesting to mention the fact that the steel ribs are never the same in dimensions due to the continuously changing tunnel section. Moreover, their foundation may have to be strengthened with micropiles and elephant foot. Since it is quite common to leave a core of 1 m at the face for safety, driving in the micropiles and placing the ribs can be tedious work. Finally, a temporary invert may be required, especially when the construction takes place in urban environment.

4. EXAMPLE CASES

There are of course many cases of constructing bifurcations, cross-overs and widening sections. Some examples –road and rail- of bifurcation chambers built with the NATM method are given here in order to demonstrate the various dimensions, difficulties but also the need for this type of construction.
4.1 Prague

Mrázovka twin tunnels in Prague are designed as a part of the city highway system and form an environmentally conscious solution to the increasing levels of traffic in the Czech capital. It is formed by two three-lane tubes that fork into a two-lane and single-lane tube in the driven tunnel forking. The tunnel was driven with the NATM method. The cross-sectional area of the single lane is 82 m$^2$, the two-lane tube is 107 m$^2$ and 160 m$^2$ for the three-lane. It is probably more famous for the difficult underpass of the Ostrovskeho Street where a number of five-storey houses are located, the total height of overburden being 16 m of which 9 m were rather weak sandy clay slates.

However, another interesting point was also the excavation of bifurcation chambers with a cross section from 160 up to 324 m$^2$. The subsoil consists mainly of clayey and silty shales while all of the rock conditions encountered by the Mrazovka tunnel are characterized by a considerably different degree of weathering, changes in direction and pitch of bedding surfaces, and numerous zones of tectonic faults. The depth of the overburden varies from 15 to 40 metres. In relation to the tunnel face, it was necessary to consider sudden changes in deformation properties of the rock mass, in both the longitudinal and the transverse direction. After the temporary support, the structural design of the final lining called for application of a closed waterproofing system and for the liner proportioning counting with a full hydrostatic head from groundwater level found up to 30 m above the tunnel crown. The waterproofing is provided along the entire circumference of all mined profiles. Finally, in terms of structural analysis is interesting to consider the design of permanent lining for a bifurcation chamber having an internal width and height of 20.5 and 11.4 m, respectively (Mosler et al., 2004).

4.2 Athens

The base stations of the Athens Metro have been in operation since the year 2000. There has been more than one case where bifurcation and widening sections had to be constructed. For example, in the Line 3 Westbound Extension to Egaleo there are both a case of bifurcation as well as transition from a double to triple track line. Table 1 contains the dimensions of this bifurcation.

The geological subsoil of Athens consists of a geological formation known as the system of the Athens Schist. The system includes clayey and calcareous sandstones, greywackes, siltstones, limestones and shales. Local lithologic transformation and significant deformation of the pre-existing members, intense folding and thrusting, widespread weathering and alteration of the...
deposits are responsible for a highly heterogeneous and anisotropic rock mass especially in the scale of the tunnel works.

Table 1. Tunnel dimensions at the bifurcation in Line 3 of the Athens Metro.

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Height (m)</th>
<th>Width (m)</th>
<th>Cross-section (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single track</td>
<td>7</td>
<td>6</td>
<td>42</td>
</tr>
<tr>
<td>Double track</td>
<td>7.8</td>
<td>9.4</td>
<td>65</td>
</tr>
<tr>
<td>Triple track</td>
<td>11</td>
<td>16.5</td>
<td>160</td>
</tr>
</tbody>
</table>

4.3 Copenhagen

Copenhagen Metro is the first underground mass transport system in operation in Denmark. The Metro runs underground for a length of 8 km under the central part of Copenhagen where several buildings of national and cultural heritage are located. The tunnels are for the greater part running in a limestone containing hard flint layers and in the outer sections where the alignments raise the tunnels are located in mixed faces of limestone and a clayed sandy till. TBMs were used while NATM tunnelling was limited to parts of the alignment where non-circular cross sections are required, for excavation in the limestone for the emergency shafts, and for excavating an underground cross-over cavern, TBM launch chambers, two bifurcation chambers and cross passages (Eskesen and Kampmann, 1998).

Fig. 5. A 17 m wide NATM chamber for a bifurcation in the Copenhagen Metro.

5. CONCLUSIONS

The construction of a bifurcation or of a gradually widening tunnel section, especially in poor ground, is a technically high demanding part of a tunnel. Conventional tunnelling is usually employed for such a task. Underground openings of larger size require more excavation phases and support measures but also offer more space for heavier and more productive equipment to be used while experienced personnel and correct choice of equipment can be vital and minimize the unavoidable delays. Conclusively, it is a task that requires conceptual skill and experienced personnel.

REFERENCES

