Urban tunnelling challenges & progress

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CHALLENGES OF URBAN TUNNELLING

In general, any tunnelling project – urban or otherwise - requires three steps in preparation and design. These steps are:

a) Selection of a tunnelling system (a tunnelling method with or without additional measures including eventual ground conditioning) which is suitable for and compatible with the given ground;

b) Cost and risk analysis to determine the optimum choice for cases where more than one tunnelling system is applicable;

c) Detail design of tunnel which usually involves:

1) estimation of loads on the liner

2) structural design of the liner

3) prediction of ground behaviour and deformations

4) selection of measures to control ground behaviour.

While all the steps above are important, in the case of urban tunnels it is usually the ground behaviour and ground control which eventually become the governing criteria of design. This involves both the ground stability and ground deformation and, above all, their conseqences – the surface settlement.

Reasons for this are most obvious, nevertheless it would be appropriate to reiterate them here. Urban environment is extremely sensitive to any type of infringement, interference and pollution. Many of these intervening factors are controlled by legislative regulations, others simply by public concern or political pressure. The fact is that the public has grown increasingly concerned about activities which may impact on their neighborhoods or their cities. Excavation of underground space is definitely one of those activities.

PROGRESS OF URBAN TUNNELLING

The engineering of underground space has recognized the above challenges for more than three decades. The past efforts can be roughly divided into the following categories:

1) Theoretical studies focused on the complex ground-structure interaction involved in excavation and support of underground space, on sources of loss of ground and on the mechanics of loss of ground distribution throughout the overburden and particularly on surface;

2) Development of the Observational Method as a way of design and construction control and as a warning system against unacceptable behaviour;

3) Practical development in ground conditioning such as various types of grouting, freezing and ground water lowering;

4) Development of tunnel boring machines with positive face control such as the slurry and earth pressure balance TBM.

LIMITS OF SURFACE DEFORMATIONS

In addition to the developments above, studies have been carried out in the areas of foundation and structural engineering to determine the values of surface deformations admissible for different types of structures. These values depend on the type of structures, their condition and their operational requirements. They are usually expressed in terms of a slope of a non-uniform settlement profile rather than in absolute values. The theory of foundation engineering recognizes two limit states of a settlement profile slope:

a) the structural limit state, when the structural integrity of a building is compromised ;

b) the operational limit state, when some essential functions of building are at risk.

Of the two limit states it is usually the second one which is applied to design of a tunnel. Specific values of limit state settlement profile slope are given in most standards or codes of practice of foundation engineering and will not be discussed or reviewed here. In this context, it is important to realize that these values are of a semi-empirical nature, derived from field measurements and supported by theoretical analysis. Irrespective of their sources (USA, Great Britain, Russia and others) the standardized values of surface settlement limit slopes differ very little, which supports their credibility.

GROUND RESPONSE TO TUNNELLING

As discussed above, the design of urban tunnels requires, among others, the prediction of the magnitude and distribution of the loads on the lining and of the displacements throughout the surrounding ground, including settlements at the ground surface.

Several methods were proposed in the past to predict the lining load and ground displacements. Most of them deal with these two predictions separately, using different semi-empirical and/or analytical methods, both for the settlement and lining predictions. The separation of the problem of displacement from the problem of lining pressure is convenient analytically, but is entirely artificial. In reality, soil displacements are closely linked to soil pressures. Although this interrelation is well known through the convergence-confinement concept its full appreciation in the practice of shallow tunnel design is not always apparent. As a consequence, many design approaches incorporated inconsistent and even conflicting assumptions, which simultaneously lead to higher lining loads and larger settlements than actually observed.

By recognizing these limitations in current practice new approaches to the problem have been attempted, which accommodated the dependency between stresses and displacements. These new approaches are based on the concept of ground and support interaction and the tunnel and the surrounding ground are modeled analytically using the finite element method. The results usually provide both the ground displacements and the lining loads. While major progress has been made in this area, major challenges still remain. One of them is the modeling of the extremely complex interaction between the ground and the tunneling method, particularly in the case of Tunnel Boring Machines (TBM) with positive face control, such as the Earth Pressure Balance (EPB) and the slurry TBMs.

DEVELOPMENT OF OBSERVATIONAL METHOD

The Observational Method (OM) is eminently well suited for tunneling. Tunnels are line structures, allowing for modifications in design and construction during their excavation.

The progress of the OM has been made mainly due to the rapid advancements in the areas electronics, data processing and measuring techniques in general. The developments in these areas were then transferred to tunneling.

The Observational Method in tunneling usually follows some or all of these goals:

1) Verification of design - where design assumptions are checked and modified during excavation of a tunnel, with positive consequences for safety and economy of the project.

2) Quality control of construction - as a method of control of contract specification.

3) Warning system against major failures or collapses - as such events seldom come without some prior indications, the OM can serve as a warning system providing the measures data are continuously interpreted.

GROUND CONDITIONING

In tunnelling, the selection of an appropriate tunnelling method usually involves one of the two following approaches:

a) either a tunneling method is selected, which is suitable for and capable of controlling the given ground

b) or the given ground is conditioned to be suitable for and controllable by the selected tunneling method.

The first approach (sub a)) will be discussed in the next section of this paper. It is the second (sub b)), which leads to ground conditioning. Major advances in this category included:

1) grouting of soil or rock mass voids in order to improve ground properties;

2) jet grouting to improve properties of ground with voids difficult to be penetrated by a grout;

3) compensation grouting to compensate for loss of ground due to tunneling and to control surface settlement;

4) compaction grouting to prestress the ground prior to destressing due to tunnel excavation.

5) freezing, as a temporary measure to stabilize otherwise unstable ground;

6) ground water lowering.

The progress in the above categories has not been uniform. Major advances were recorded in categories 1) to 4). However, these methods of ground conditioning still depend to a large degree on skills and experience of their providers and on quality of the work. These methods, so far, resisted any development of a scientific background and still remain largely empirical.

TUNNEL BORING MACHINES WITH POSITIVE FACE CONTROL

The ultimate dream of mechanized tunneling is a TBM capable of handling any type of ground. While fulfilling of such a dream is still somewhere in the future, the development of TBMs with positive face control has been a major step in that direction.

The present state of application of tunneling technology for shallow, urban tunnels in soft ground has been clearly dominated by tunnel boring machines (TBM) with positive face control. This category includes three types of TBMs - earth pressure balance (EPB) TBM, bentonite slurry (BS) TBM and a TBM with compressed air (CA). The third type (CA) used to be the only positive face control technology available prior to the development of the EPB and BS techniques, however presently is gradually getting extinct in tunneling practice because of difficult working conditions associated with its application. Thus it is the first two types (EPB and BS) which convincingly prevail in soft ground urban tunnelling. Both types are clearly preferred over open face TBMs and non-shielded methods such as the New Austrian Tunneling Method (NATM), because they offer far better ground control. In urban environment ground control is of paramount importance, since it directly affects surface settlement and as such often represents the governing design and construction criterion.

While both the EPB and BS TBMs can deliver a positive face control during tunnel excavation, they differ fundamentally in the way this control is provided. The EPB TBM pressurizes the face of the excavated tunnel by stresses transmitted by the reworked soil cuttings present in the front chamber. The face support is thus of the earth pressure type and as such is deformation dependent. Because the soil cuttings are removed and the soil pressure is released mechanically through a screw conveyor, the EPB can only work in either a total stress or an effective (grain to grain) stress mode. It cannot support neutral (water) pressure inside the front chamber.

The BS TBM provides stress at the face hydraulically by bentonite slurry kept under pressure in the front chamber. The slurry penetrates some distance into the supported soil and creates a membrane against which the pressure is maintained. Thus the BS TBM can control either a total stress or a neutral (water) pressure. It cannot support directly the effective stress in the front chamber.

This difference in the mechanics of the face support has a direct impact on the applicability of the two TBM types. The EPB TBM can successfully control and support a tunnel face in either a dry or a saturated fine grained soil, where no free water is present in the front chamber. On the other hand, the BS TBM can reliably operate in practically all types of soils, fine or coarse grained, with or without free water. This is because free water can be effectively countered by the pressurized bentonite slurry.

Both types, when applied in proper ground conditions, can deliver a ground control superb to most other tunneling technologies. This is why they presently account for majority of urban tunnel construction.

SUMMARY

Despite enormous progress during the last 30 years urban tunneling remains one the greatest challenges of underground engineering. Environmentally sensitive cities and their inhabitants place ever growing demands on this type of activity. Future progress will take place in several directions, with the development of universal TBMs at the forefront.