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A rational approach to model the ground movements around a tunnel boring machine

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ABSTRACT

Tunnelling in the urban environment requires an accurate assessment of ground movements around the tunnel boring machine (TBM) to assess any potential effect on the existing infrastructure. Most of the modern finite element method (FEM) modelling techniques prescribe the deformation pattern around the tunnel excavation caused by the TBM known as gap modelling. Standard, uniform and oval-shaped volume loss models have been developed earlier by various researchers, which are used extensively to simulate TBM tunnel excavation in FEM/FDM modelling.

This paper presents a new approach to simulate tunnel movements associated with TBM excavation as an alternative to prescribing the deformation boundary condition around the tunnel. The proposed FLAC modelling (functional control) technique allows the tunnel to deform naturally and gradually during excavation as the TBM passes through the section. Tunnel stability is maintained using a FISH routine developed based on the characteristics, functional aspect and different phases of the TBM excavation cycle. The proposed modelling technique allows the tunnel to deform slowly, so that the unbalanced forces are distributed throughout the model, in order to provide a more accurate representation of the modelled volume loss.

A case study based on TBM tunnel excavation completed for the Delhi Metro Rail Corporation (DMRC) project is presented, and the results are discussed in comparison with the uniform gap modelling technique, empirical methods and field observation data.
Keywords: TBM Tunnel, Volume Loss, Face Loss, Subsidence, FLAC.

1 INTRODUCTION

Based on the virtual image technique, Sagaseta (1987) proposed the solution for the ground loss (also known as volume loss- VL) in incompressible soil, and this was further extended by Verruijt and Booker (1996) for a tunnel in a homogeneous elastic half space. An analytical solution for a circular tunnel in an elastic half plane was developed by Verruijt and Booker (1996), Verruijt (1997) and Bobet (2001), based on the concept of prescribed uniform radial deformation (Figure 1) to represent volume loss. Loganathan and Poulos (1998) proposed an oval-shaped ground deformation pattern around the tunnel boundary for the short-term undrained condition. They proposed an exponential function which is the equivalent to the undrained ground loss and developed in accordance with the gap parameter approach proposed by Lee et al. (1992).

Recently, Park (2005) modified the elastic solutions of Verruijt and Booker (1996) to predict the tunnelling induced ground deformation in clayey soils for four different deformation patterns as prescribed boundary condition on the tunnel opening, and compared them with five other case studies.

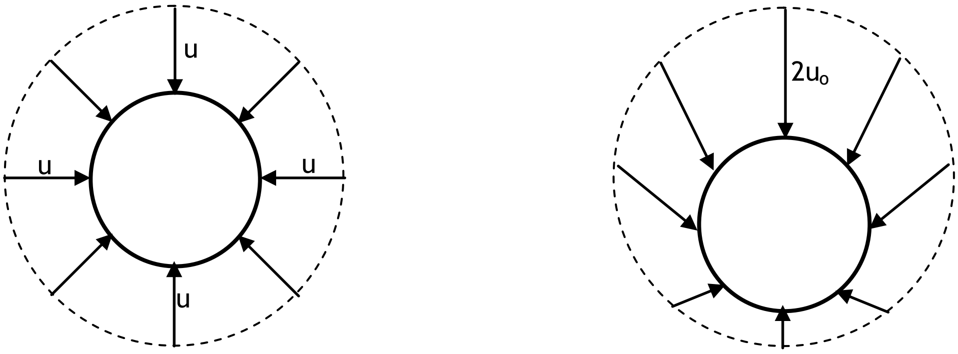


Figure 1: Uniform and oval-shaped volume loss model as proposed by Sagaseta (1987), Verruijt and Booker (1996), Loganathan and Poulos (1998), Bobet (2001)

2 DEVELOPMENT OF A NEW MODELLING TECHNIQUE

Historically, most of the numerical modelling techniques have adopted the simple circular or oval-shaped gap parameters for simulating the ground movement around the excavation and predicting the surface settlement. These models do not allow the ground to deform as per the insitu conditions. They also impose a predefined condition on excavation boundary while calculating the surface settlements.
The following sections describe the basic characteristics of the TBM and basic idealisation of the newly proposed modelling technique. The total volume loss and related surface settlement with respect to the TBM movement in soil are also elaborated.

2.1 Characteristics of a TBM

The cutter head situated at the front of the TBM, has a diameter slightly larger than the rest of the TBM (i.e. shield and liner). The stability of the excavated face in front of the cutter head is maintained by applying uniform earth pressure all over the face. In large diameter TBM tunnels, the ground pressure is different at invert and crown levels, thus leading to soil deformation due to unbalanced force over the excavated face.
Though the TBM shield has a cylindrical (constant diameter) appearance, it has the shape of a cone with the diameter of the front end being slightly larger than that of the tail. The difference in diameter may be small (in the order of a few millimetres), but is significant to enable the TBM to manoeuvre in the soil. As the TBM advances, it allows the soil to settle/deform around the shield at a slow rate and also decreases the stresses in the soil around the TBM.

Grouting around the liner is done either through the tail skin or from the grout port in the liner. At the grout interface, two different types of settlement take place. Where grouting is done from the grout ports on segments, closure of the ungrouted gap at the tail of the TBM is significant and instantaneous (especially in sandy soil condition). Second stage deformation occurs after the gap is fully grouted due to the redistribution of the green grout in both types of grouting arrangements.

2.2 Settlement and Volume loss along the TBM length

As reported in AFTES (1999), total surface settlement and related volume loss are divided into three different stages, namely face loss, shield loss, and tail loss, as shown in Figure 2. After the TBM passes the section, ground-liner interaction (soil-structure interaction) takes place which further influences the surface settlement. It is necessary to estimate the expected tunnel ground loss before the magnitude of surface settlement can be predicted. This estimate will be based on case history data, and should include an engineering appraisal that takes into account the proposed tunnelling method and site conditions. Based on field observations AFTES (1999) suggests the distribution of the surface settlement at various stages of TBM operation, and hence the volume loss around the TBM should be in the order as given below:

- Stage-1 Face Loss: 10 to 20% by the face
- Stage-2 Shield Loss: 40 to 50% by the void along the shield
- Stage-3 Tail Loss: 30 to 50% at the end of the tail seal
- Stage-4 Ground Liner Interaction: based on interface condition

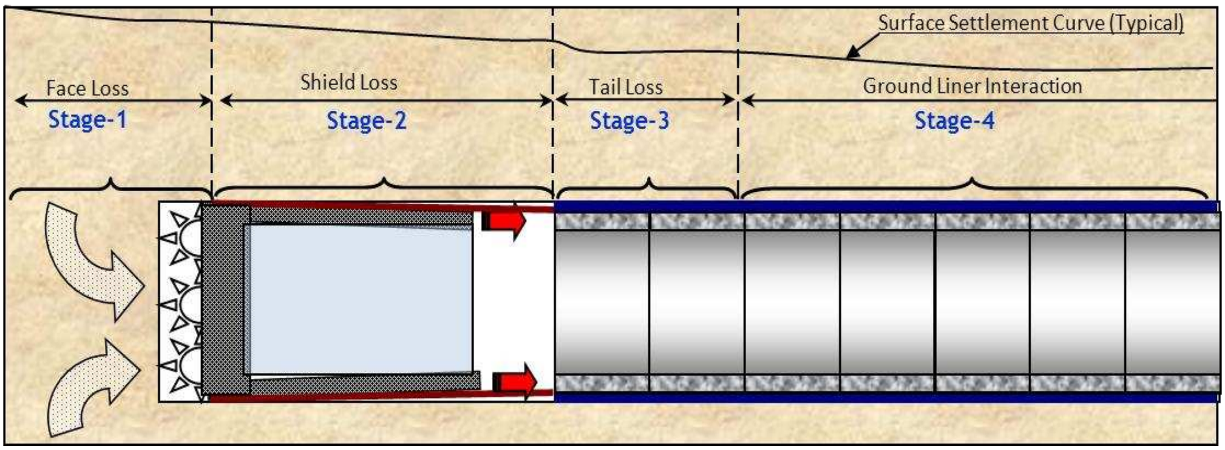


Figure 2: TBM Longitudinal section and surface settlement profile

3 DESCRIPTION OF NUMERICAL MODEL

FLAC (2005) is an explicit finite difference program which has been adopted for numerical modelling. The following sections describe the conceptualisation of all the four modelling stages that contribute to surface settlement.

3.1 Stage-1: Face Loss

In general, face loss displacement is an inward displacement of the ground, ahead and around the cutter head, due to stress relief. The displacement occurs ahead of the face. The face loss is simulated by stress controlled relaxation of the tunnel section using a module in FISH language. The FISH function is written in such a way that it gradually reduces the unbalanced forces until the desired face loss limit is reached. It is worth noting that this function does not apply to any predefined condition on deformations, and the pattern/shape of deformations is governed by the insitu conditions.

3.2 Stage-2: Shield Loss

Literature suggests that shield loss is the most significant, and accounts for up to 40 to 50% of the total volume loss during the complete construction process. Tapering of the shield allows the surrounding soil to deform in a uniform manner, and this deformation is controlled by the geometry of the TBM and its advancement rate. In other words, this could be called the strain-controlled behaviour/deformation in this technique.
As shield-loss is not an instantaneous deformation, the effect of the displacement will be well distributed rather than localised as in face loss. In order to model this behaviour, a special FISH function has been written, which controls the deformation in the section and not the stresses. This function allows the model to deform slowly (as the TBM tapers), so that limited unbalanced forces develop in the model, and the effect could be well distributed.

3.3 Stage-3: Tail Loss

Forward movement of the shield over the liner leaves a gap between the liner and soil. Also, green grout around the lining has some compressible nature which allows the soil to deform freely. In this proposed method, the tunnel is allowed to deform in a non-uniform manner under the effect of insitu conditions. The tunnel is made to deform in a controlled manner by the gradual reduction of the unbalanced forces in the tunnel boundary until the desired face loss limit is reached.

3.4 Stage-4: Ground Liner Interaction

This stage of the model reflects the ground movement along the interface as well as the behaviour of the lining deformation. In many modelling techniques, liner extrados are simulated to make the model accountable for the gap parameter (thickness) on the excavated boundary. In this proposed modelling technique, centreline of the liner is simulated, and the gap between the liner centreline and grout extrados is connected by the elastic interface.

4 CASE STUDY: DELHI METRO TUNNEL

A case study has been carried out on a rail tunnel in New Delhi, India constructed by the Delhi Metro Rail Corporation (DMRC). The geometric and geotechnical details of rail tunnels have been adopted from Yadav (2005). Typical section at reference line No-11 has been adopted for analysis. Geometric and geotechnical details of this location are shown in Figure 3. The decision to select reference line No-11 was based on the consistency of the field observations. The observations were more systematic, uniform and representative in comparison to observations on other reference lines. The tunnels pass through the flat alluvium deposits generally know as Delhi Silt. The older alluvium in this area consists of fine grained deposits and kankars (calcareous nodules).

Staged construction of the twin tunnel has been adopted in both the FLAC modelling techniques. Excavation to lining installation (Stage-1 to Stage-4) sequence for tunnel T-1 is carried out prior to excavation sequence for tunnel T-2. In order to simplify the modelling, this paper does not consider any possible variations of interface condition, and only prescribes the simplest elastic spring model for all the modelling methods and cases considered in this paper.

Sensitivity analysis has been carried out for 1.5%, 2.0% and 2.5% VL models as per proposed functional controlled modelling and gap element (1.5%-24mm, 2.0%-32mm and 2.5%-40mm) modelling. Results are only shown for 2.0% VL model, which is compared with the empirical method as suggested by Peck (1969) and field monitoring observations. In function controlled modelling, this paper has assumed face loss as 10%, shield loss as 60% and tail loss as 30% of total volume loss. As mentioned before, this paper emphasises the technique of modelling, and these ranges could be changed or optimised based on the more accurate field data.

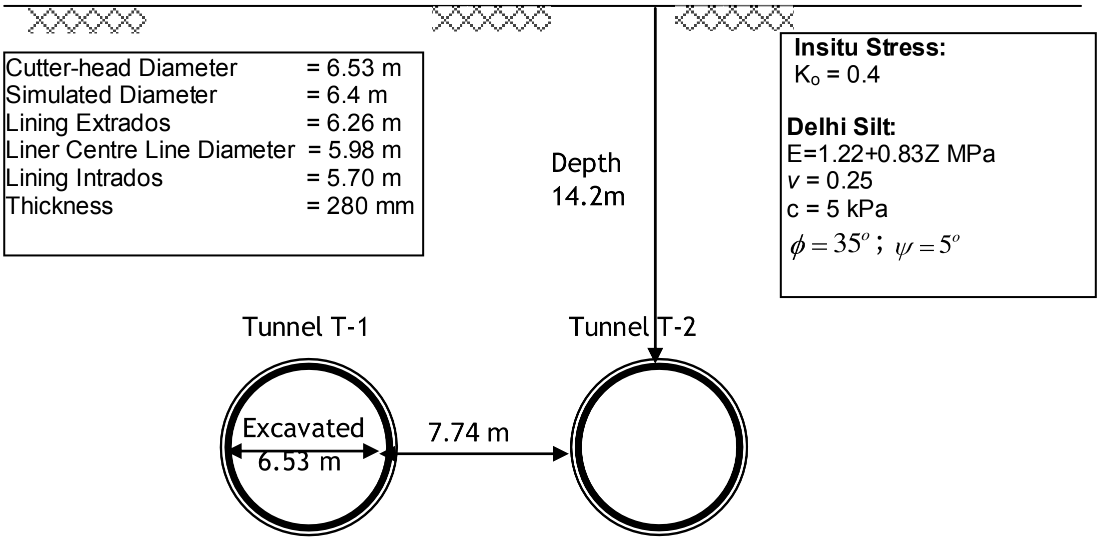


Figure 3: Geometry and Properties of Delhi Metro Tunnel section

In gap element modelling, the gap equivalent to the volume loss model is created between the liner and excavated soil boundaries for a given diameter of tunnel. It should be noted that a gap has been created with respect to the adopted excavated boundary (6.4 m), and the simulated liner has a radius higher than the actual diameter of the liner.

In functional control modelling, equivalent average deformation (i.e. volume loss) has been generated by function in three separate predefined stages. This allows the model to simulate the centreline of the liner, and the gap between the liner centreline and deformed excavated boundary is connected by the elastic interface, and hence a more accurate liner and interface response is simulated in the model.

5 RESULTS AND DISCUSSION

5.1 Volume loss and induced settlement

Table 1 shows the single tunnel deformation for both the modelling techniques, the Stage-4 results of function control modelling (average 35.2mm) compare well with the results from the equivalent gap model (average 35.6mm).

Table 1: Summary of Single tunnel deformation (mm) in different stages

Descriptions		**Functional Controlled Modelling**				**Gap Element Model**	
		Stage-1	Stage-2	Stage-3	Stage-4	Prescribed	Converged
V_L=2.0%	Crown	5.3	26	48	55.9	Uniform gap of 32mm	45.3
	Sides	1.2/1.3	20.7/20.8	28.1/28.2	19.3/19.6		22.6/23.2
	Invert	5.2	24.6	41.1	51.9		56.1
	Average	3.3	23.0	35	**35.2**		**35.6**

As volume loss is controlled, so is the surface settlement, and the unbalanced forces (or strains) generated at the excavated boundary are continuously distributed around the excavation and towards the surface. Figure 4 shows the volume loss and surface settlement plot as the TBM excavation progress. Section 5.2 further discusses the effectiveness of the gradual increment of volume loss.

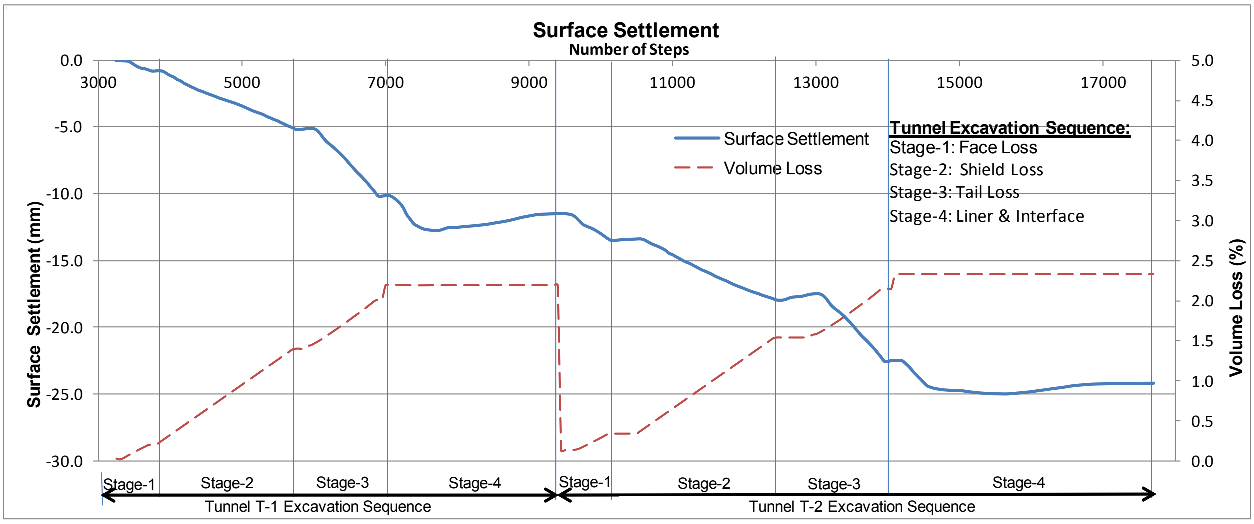


Figure 4: Volume loss and induced surface settlement due to tunnel excavation/advancement

5.2 Comparison with other methods and field data

The results of the modelling techniques are compared with the empirical method as proposed by Peck (1969) and with field monitoring observations Figure 5 which shows the surface settlement induced due to staged construction defined through Stage-1 to Stage-4 for tunnel T-1 followed by Stage-1 to Stage-4 for Tunnel T-2.

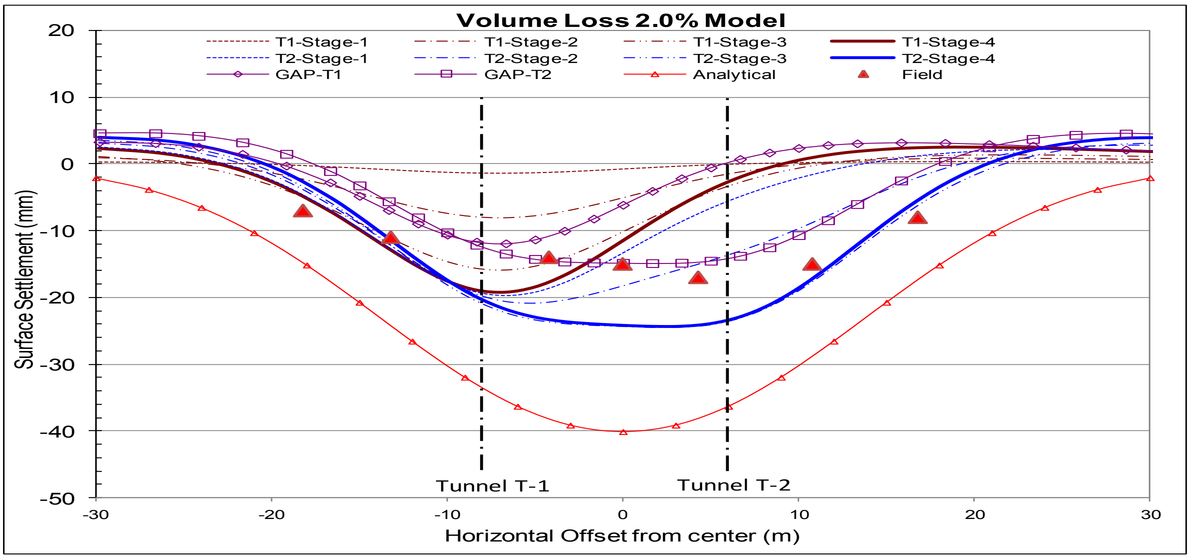
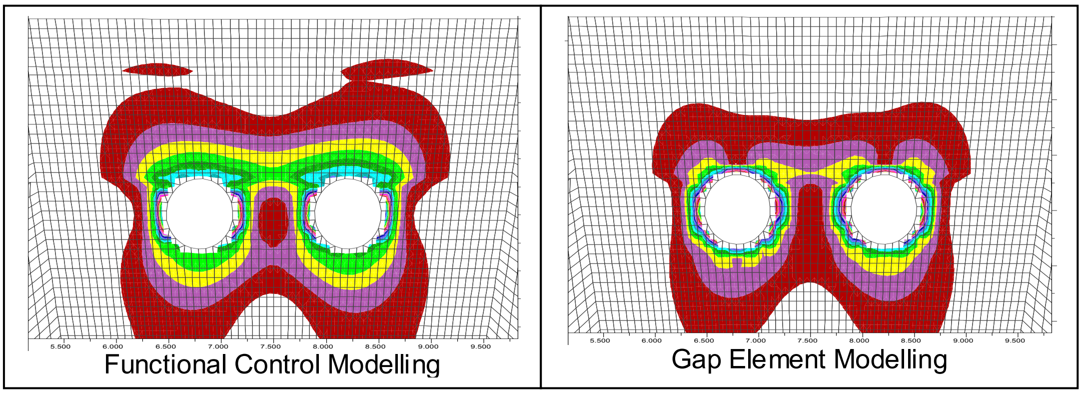


Figure 5: Comparison with other methods and field monitoring data (2.0% VL model)

Figure 5 show that functional control modelling predicts lower values of surface subsidence (25mm) compared to the 40mm from empirical method. This is because of the higher insitu stress ratio (K_o=0.4) adopted in the FLAC modelling technique. The empirical method, does not account for the stress ratio. Moreover, the empirical method is based on the simple arithmetic sum of both single tunnels, and does not account for any influence of tunnels over each other. The numerical modelling techniques, on the other hand, incorporate the influence of the tunnels on each other, and hence are expected to more accurately reflect the interaction.

Figure 5 also indicate that the gap element modelling predicts smaller surface settlements as compare to field data. This is due to the gradual increment of the VL. Material softening around the excavation can be clearly seen in Figure 6 of shear strain increment plot around the excavation at final stage for both the modelling techniques. Figure 6 clearly indicates that functional control modelling predict a wider influence area (~1.5D) compared with the gap element modelling (~1D). As noted and shown in Table 1, the average tunnel deformations (i.e. volume loss) for the final stage (Stage-4) are the same in both the modelling techniques.



Functional Control Modelling

Gap Element Modelling

Figure 6: Shear strain increment around tunnels indicating tunnels influence area

Field monitoring data are also shown in Figure 5. The functional controlled monitoring (for 2% VL) clearly encircles the observed field data. There are many uncertainties and limitations in prediction of VL, and more often an estimated/engineering assumption is the basis for predicting the VL at any given location/time. Considering the large diameter of tunnels, 2.0% VL is the expected to be at the upper end of the range for the modern EPB machines.

6 CONCLUSIONS

The presented modelling technique is very closely and rationally based on the rationalisation of TBM characteristics and tunnelling aspects. The function control modelling technique described herein can be briefly explained as a boundary condition applied by the TBM on tunnel excavation boundary with respect to time or forward motion of TBM. The proposed modelling technique allows for the tunnel to deform slowly and gradually so that strain developed at the excavation is distributed throughout the model in order to provide a more accurate representation of the modelled volume loss compare to gap modelling technique.

Most importantly, tunnel deformations predicted using the presented method can also take into account the existing infrastructure in the vicinity of the tunnel. This paper demonstrates that the proposed method could be used to simulate multiple tunnel openings in close proximity and simulat the interaction on each other. The method can also be used for non-standard tunnel sections where standard references are not available.

The proposed modelling technique has been recently developed and uses the complex FISH routine which needs additional skills and resources to develop. The proposed function control method will be further refined and possibly incorporated as a built-in feature in software packages.

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