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Modified gap method for prediction of TBM tunnelling-induced soil settlement in sand - a case study

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ABSTRACT: The development of tunnelling projects for new transportation systems in many urban areas is an inevitable trend because of the increasing shortage of over ground space in the built environment. A critical problem in tunnel construction is the induced ground deformations that may cause serious damage to surrounding structures. Therefore, realistic prediction of tunnelling-induced ground movements is very important to ensure operational safety for surrounding buildings. Finite element analysis is among the common methods that has been used widely for prediction of ground movements caused by tunnel excavation. However, one of the common drawbacks of finite element analysis in tunnelling is the obtained settlement curves are often wider than those in practice especially for shallow tunnels. This paper proposes a modification to the original gap method to take into account the deformation mechanism of sand soil around the tunnel boundary. A series of finite element analyses using different tunnel excavation simulation approaches, including the gap method and the modified gap method, have been carried out to back-analyse surface settlement caused by tunnelling in sand in line Number 1 Ben Thanh - Suoi Tien in Ho Chi Minh city, Vietnam. The field measurements are used to evaluate the performance of each approach. It was found that the modified gap method proposed in this paper provided closer prediction to the measured soil settlement.

1 INTRODUCTION

Key factors influencing the performance of Finite Element Method (FEM) calculations include boundary conditions, the constitutive soil model, and simulation of the construction process.

1.1 Boundary conditions

Boundary conditions play an essential role in the numerical modelling of the behaviour of the entire soil mass. The size of the mesh should be chosen so that it is not too small, as that might impose restrictions on the predicted soil deformations, or too large, which increases calculation time.

Regarding the size of the FE mesh in the transverse direction, it is noted that soil movements can extend up to 3*i* where *i* is the settlement trough width parameter (O'Reilly & New 1982) and that the mesh would need to extend beyond this distance. In the vertical direction, Taylor (1995) suggested that the depth of the model soil below the tunnel invert needs to be larger than one diameter of the tunnel to minimise any potential boundary effects.

1.2 Constitutive soil model

Choosing a constitutive soil model is critical to any FEM so that the particular features of soil which are important in the simulated case can be reproduced (Wood 2004). In the past three decades, some advanced soil models have been developed and proved to be capable of simulating the non-linear response of soil and the effects of stress path history such as the three-surface kinematic hardening (3-SKH) (Stallebrass 1990, Stallebrass & Taylor 1997), the modified three-surface kinematic hardening (M3-SKH) (Grammatikopoulou et al. 2008), and the Hypoplastic Cam-clay model (Masin 2012).

Such advanced constitutive soil models require at least 8 parameters in which certain parameters can only be obtained through calibration and are not common in industry. Therefore, simpler constitutive soil models, such as the Mohr–Coulomb are often adopted in practice (Amorosi et al. 2014).

1.3 Simulation of the tunnelling process and induced ground movements

Tunnelling is a complex three-dimensional process which is normally simplified in FEM. According to

Potts & Zdarkovic (2001), there are three main approaches to model ground movements induced by tunnelling in FEM as described below.

1.3.1 Reduction of soil stiffness within the tunnel heading

The first approach is the 'progressive softening' method which was developed for modelling of the New Austrian Tunnelling Method (NATM or sprayed concrete lining tunnel). In this method, the soil within the tunnel heading is softened by applying a reduction factor to the soil stiffness. Then, the excavation forces are generated at the boundary of the future tunnel which causes deformations in the soil body that was softened.

1.3.2 Reduction of radial stress at the tunnel perimeter

The second approach, including the 'convergence-confinement' and 'volume loss control' methods, involves progressive reduction of the radial stresses at the tunnel boundary to model the excavation process. The magnitude of the reduction of the radial stress is related to the desired volume loss. The tunnel lining is then installed when the desired volume loss is achieved.

1.3.3 Prescribing movement at the tunnel perimeter

This method is referred as the 'gap' method which was introduced by Rowe et al. (1983). A void that represents the total ground loss is defined in the finite element mesh. This void incorporates the out of plane and in plane ground losses, and additional losses that take into account the misalignment of the shield, the quality of workmanship, and the volume change due to soil remoulding (Potts & Zdarkovic 2001). The gap parameter is the difference between the initial tunnel diameter, D_E and the final tunnel diameter, D_T. At the tunnel invert, the gap is equal to 0 with the assumption that there is no movement in this location (Fig. 1).

At the initial tunnel perimeter, ground movements due to tunnelling is simulated by applying prescribed displacements that consists of vertical and horizontal components (Fig. 1). The prescribed displacements can be chosen to achieve the desired volume loss.

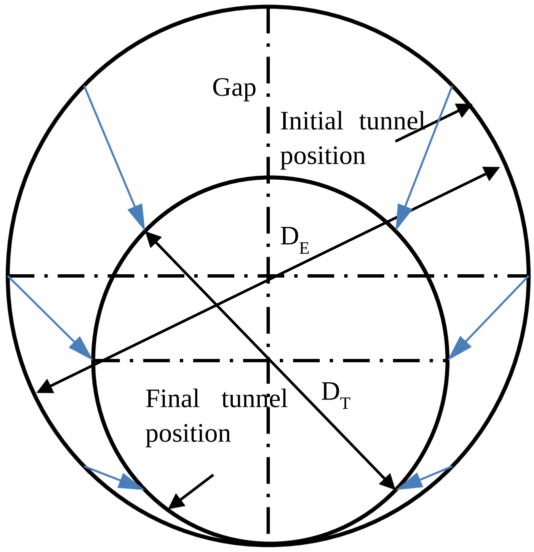


Figure 1. The gap method (After Potts & Zdravkovic 2001).

The two main reasons for the difference between the predicted and the field settlement curves are the quality of the constitutive soil model and the simulation of the tunnel construction process.

Considering the constitutive model, issues such as soil anisotropy, non-linear elasticity and plasticity and stress path dependence may be relevant. Therefore, advanced constitutive soil models are required to correctly simulate soil behaviour. Such models require additional soil parameters which are not always provided for projects in industry which hinders the adoption of these sophisticated models into practice.

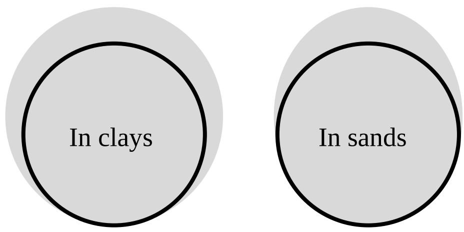


Figure 2. Typical ground loss distribution for shallow tunnels (after Franza et al. 2019).

1.4 Brief overview of the performance of FEM

The surface settlement curve due to tunnelling predicted by the FEM is normally wider than that observed in practice (Addenbrooke et al. 1997; Addenbrooke & Potts 2001, Pickhaver 2006) even when advanced constitutive soil models were adopted (Franzius et al. 2005, Grammatikopoulou et al. 2008). That in turn causes the calculated settlement trough to be shallower and underpredict the maximum surface settlement.

As regards simulating the construction process, in finite element analysis the zone of ground loss around the tunnel periphery is often assumed to be in circular shape. However, Franza et al. (2019), by means of centrifuge tests results, showed that ground loss is distributed not in a circular zone but in a roughly elliptical shape for clays and is concentrated above the tunnel crown for sands (Fig. 2). This may explain the reason for the calculated surface settlement troughs from finite element analysis being normally wider than that in practice.

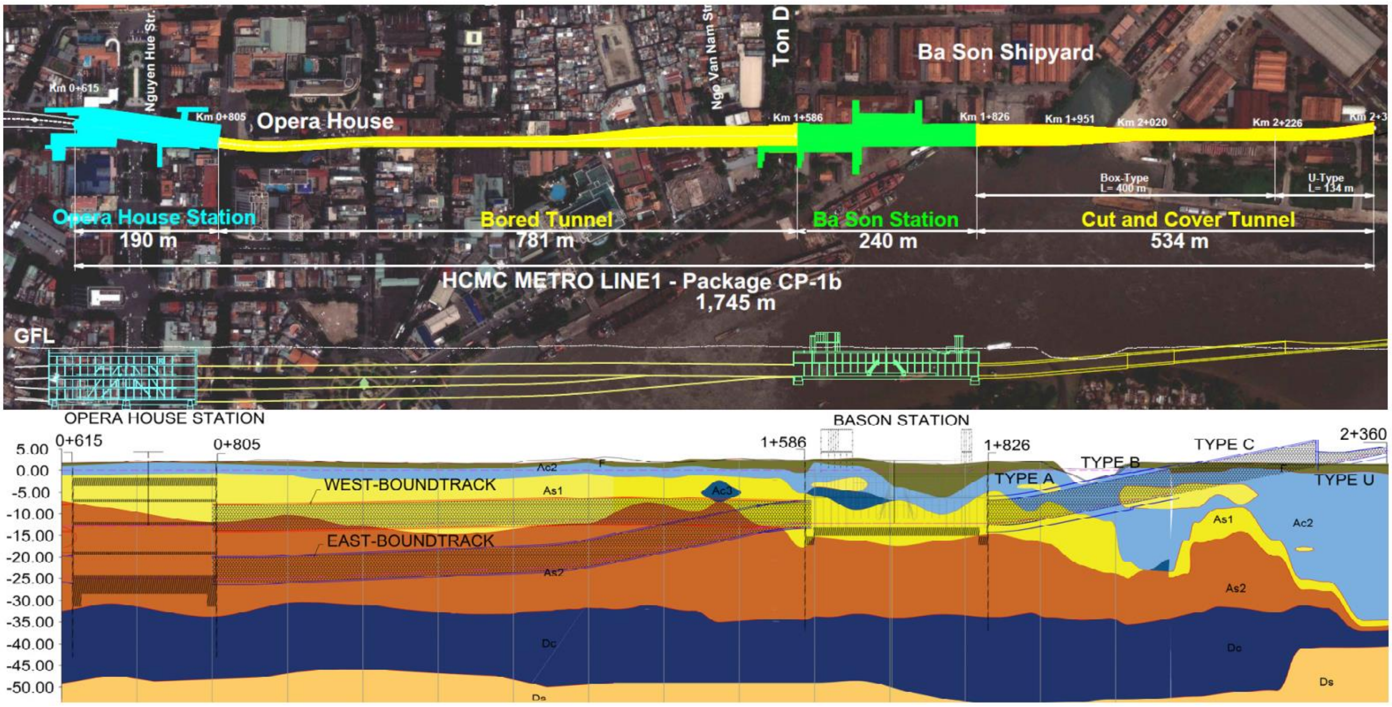


Figure 3. The underground section of line Ben Thanh – Suoi Tien (Kuriki 2008).

This paper aims to investigate how the way the ground loss around the tunnel cavity is simulated can affect the predicted ground surface settlement troughs. Finite element analyses using the original gap method (Rowe et al. 1983, Potts & Zdarkovic 2001) and a modified gap method are conducted to determine tunnelling induced ground surface settlement. The performance of those analyses will then be assessed by comparing the results with the field data from a case study.

2 THE CASE STUDY

2.1 Overall information

The case study in this paper is the tunnel section in the line Ben Thanh- Suoi Tien. This is the first metro line among the 8 lines that have been planned in Ho Chi Minh city in Vietnam. The total length of the line Ben Thanh – Suoi Tien is 19.7km which comprises 781m of twin tunnels that form part of the underground section (Fig. 3).

The tunnels were constructed from 26/05/2017 and completed on 29/06/2018 by Earth Pressure Balance Tunnel Boring Machine (EPB TBM). The TBM driving direction is from Bason station to Ben Thanh station. The average advancement rate was approximately 10m per day.

The East bound tunnel (EB) was constructed first and then the EPB TBM was dismantled and transported back to Bason station for the construction of the shallower West bound tunnel (WB).

2.2 The tunnel arrangement and geotechnical conditions

Figure 4 illustrates the tunnel position and soil conditions at the monitoring section (chainage km 1+403).

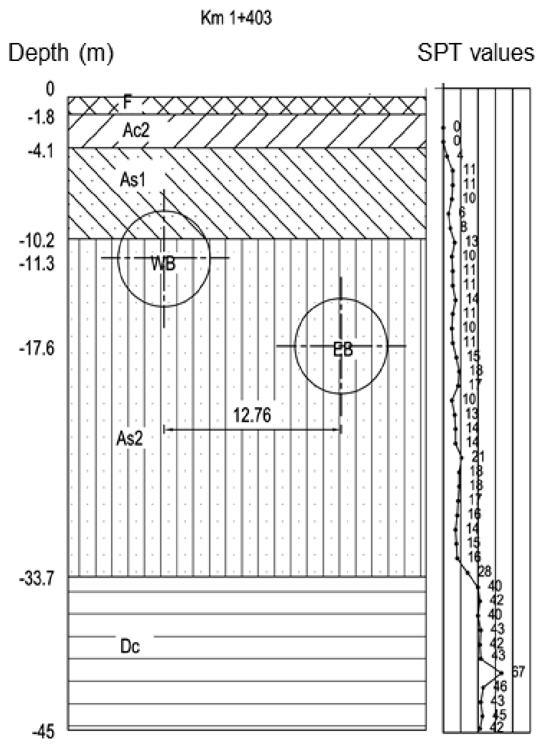


Figure 4. Tunnel arrangement and geotechnical profiles (Le et al. 2019b).

The water table was approximately 2m below ground surface. The soil in this area consists of five

different layers as illustrated in Figure 6 and described below:
- Fill: sand, clay, gravel, brick, concrete, yellowish grey, yellowish brown;
- AC2 (Alluvial clay): fat CLAY, bluish grey, very soft to soft;
- AS1 (Alluvial sand): silty SAND/clayey SAND, somewhere with organic, gravel, blackish grey, bluish grey, brownish grey, yellowish grey, medium stiff to stiff, somewhere soft;
- AS2 (Alluvial sand): silty SAND/Silty clayey SAND, yellowish grey, bluish grey, whitish grey, medium dense;
- DC (Diluvium clay): Lean CLAY/fat CLAY/clayey silt, yellowish brown, bluish grey, brownish grey, very stiff to hard.

At the monitoring sections, the EB tunnel was positioned at depth 17.6m below ground surface and was completely in the sand layer AS2. The WB is at 11.3m below the ground surface and positioned in the two sand layers AS1 and AS2. The horizontal distance between the two tunnels is 12.76m.

3 THE FINITE ELEMENT ANALYSIS

3.1 Modelling of tunnel excavation

The finite element software Abaqus was used for the analysis. The CPE4RP element was used with 4-node bilinear displacement and pore pressure, reduced integration with hourglass control. Figure 5 depicts the mesh.

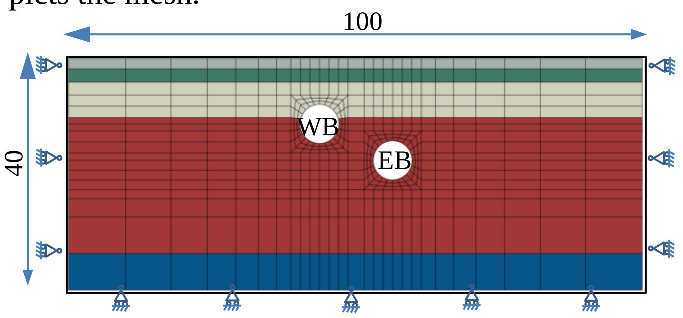


Figure 5. Finite element model in Abaqus.

The excavation process was modelled in three main stages as follows:

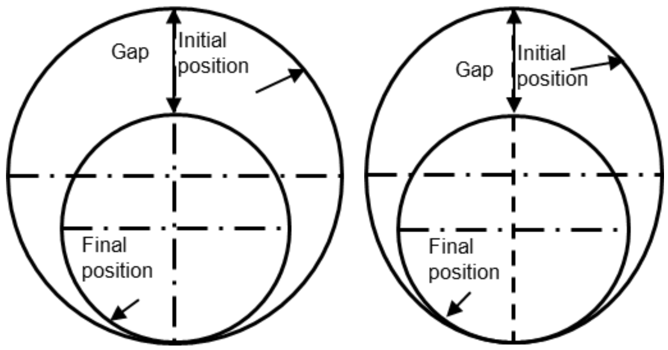
- Initialization of soil stress and pore water pressure;
- Excavation of EB tunnel: soil within the EB tunnel is deactivated. Application of prescribed displacements to EB tunnel boundary to achieve the desired volume loss; and
- Excavation of WB tunnel: soil within the WB tunnel is deactivated. Application of prescribed displacements to WB tunnel boundary to achieve the desired volume loss.

By using the gap and the modified gap methods (Fig. 6), the application of prescribed displacements was performed in several steps.

In these two methods, the displacements in vertical and horizontal directions are imposed to the nodes at the initial position of the tunnel to simulate the tunnelling-induced soil movements towards the final position such that the lowest point of the tunnel is fixed (Rowe et al. 1983, Amorosi et al. 2015, Yiu et al. 2017).

The key difference between the two methods is that the ground loss is modelled in a circular shape for the original gap method and in an elliptical shape for the modified gap method.

For ground loss simulation using a circular shape, the initial position of the tunnel is defined as the excavation area with the diameter of D_{exc}=6.82m. For the elliptical case, the tunnel initial position is defined as an ellipse with the major axis to be equal to the excavation diameter and the minor axis is the diameter of the tunnel lining D_{lining}=6.65m. The final position of the tunnel is determined when the target volume loss is achieved.



a. Original method b. Modified method
Figure 6. Original and modified gap methods.

3.2 Constitutive soil model

The Mohr-Coulomb model was adopted for the FE analyses due to the limitations in soil parameter available from the soil investigation report. Despite its simplicity which is often inappropriate in simulating complex soil behaviour, the Mohr-Coulomb model has proved to be adequate for greenfield studies (Amorosi et al. 2015). The parameters of the soils are presented in Table 1.

Table 1. Properties of soil

Layer	γ (kN/m³)	w (%)	c' (kPa)	ϕ' (°)	E (MPa)	k (m/s)
Fill	19.0	43.6	10	25	10	10-6
AC2	16.5	49.1	0	24	3	10-9
AS1	20.5	19	0	30	20.8	2x10-5
AS2	20.5	18.6	0	33	35.5	2x10-5
DC	21	19.2	N/A	N/A	106.5	10-8

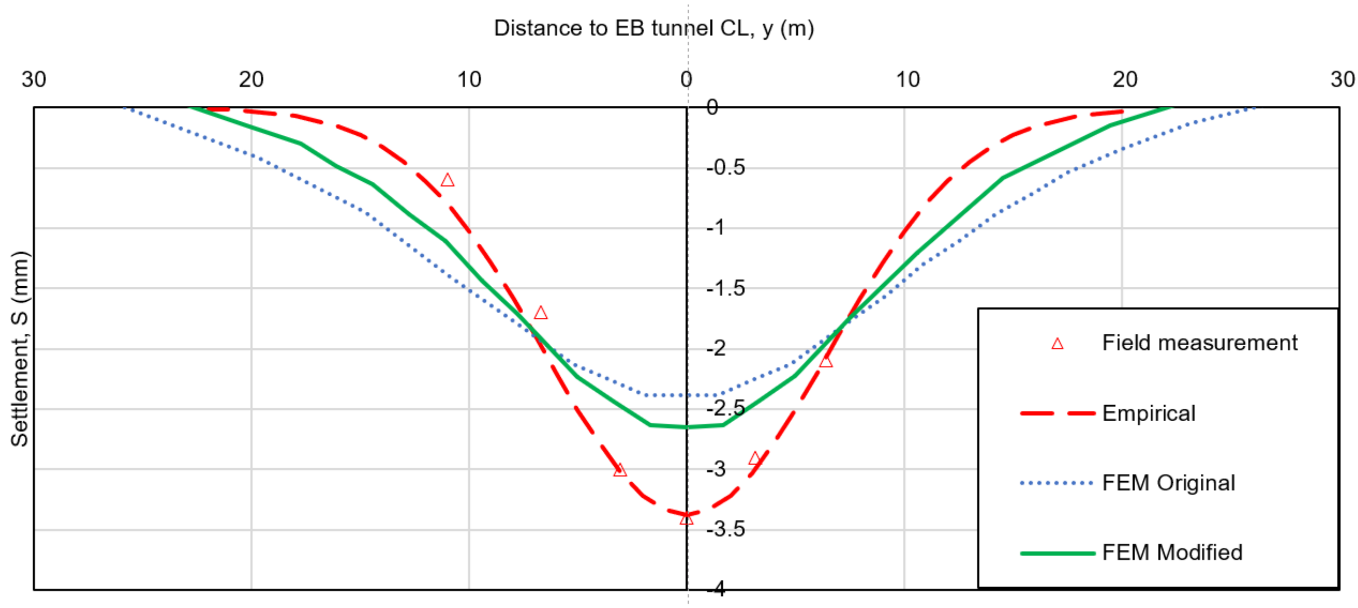


Figure 7. Ground surface settlement after EB tunnel construction.

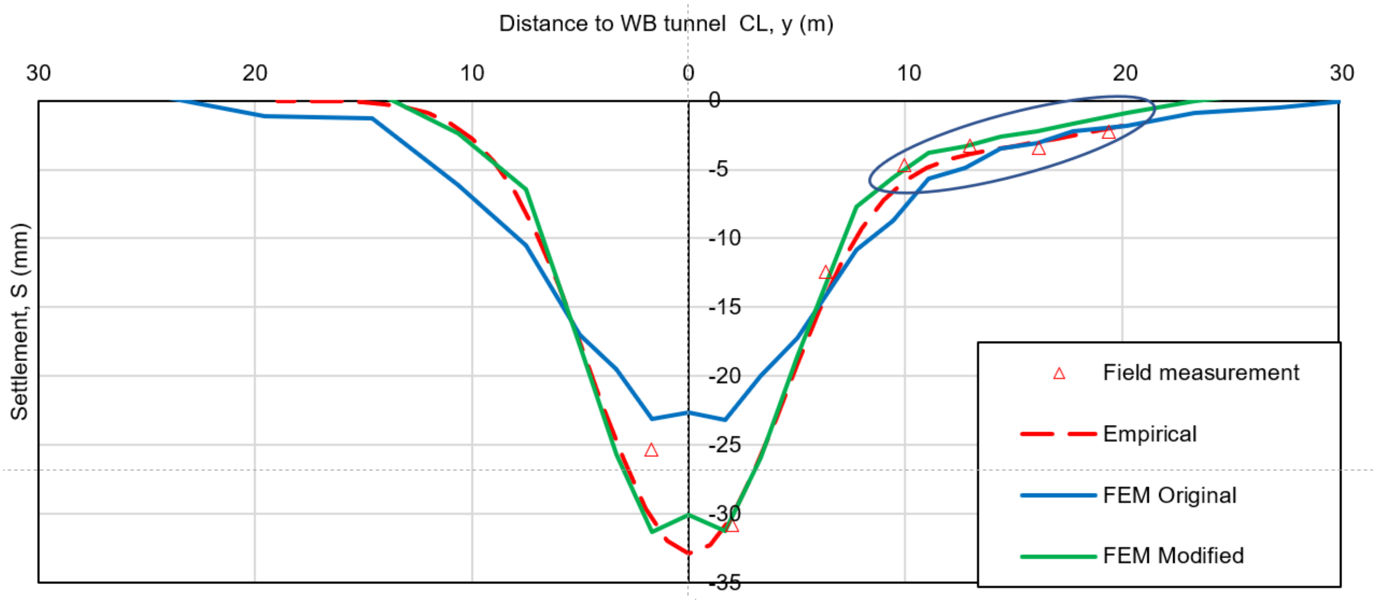


Figure 8. Ground surface settlement after WB tunnel construction.

4 RESULTS

In order to assess the performance of the two methods, Figures 7 and 8 compare ground surface settlement, induced after the construction of the EB and WB tunnels, from field measurement, empirical method and FEM analyses.

For the empirical method, back analysis using a non-linear regression approach (Jones & Clayton 2013) was adopted to determine the K and V_L values to plot the ground surface settlement trough. Details of this analysis can be found in Le et al. (2019a) and Le et al. (2019b). The calculated K and V_L values for the two tunnels are:

- For EB tunnel: K = 0.368; V_L =0.15%;
- For WB tunnel: K = 0.398; VL = 1%.

The above V_L values were used as the input for the target V_L in the FE analyses so that the determined ground surface settlement troughs have the same ground losses enabling comparisons to be made.

Note that ground surface settlement trough after the WB tunnel construction is not symmetrical as there had been settlement induced during the EB tunnel construction (marked in Fig. 8).

5 DISCUSSION

From Figures 7 and 8, it can be seen that the settlement troughs obtained from the modified gap method fits better with the measured data than that for the original gap method.

For the ground surface settlement induced by the EB tunnel where the soil settlement was small, the settlement troughs obtained from FEM analyses are still wider than that from the field measurement. The reason is that the Mohr-Coulomb soil model can only produce reasonable results for large displacements, in which the effects of non-linear behaviour of soil are less significant.

As the constitutive soil model and the V_L values in the two analyses were the same, it is evident that the improvement in the calculation of the surface settlement trough is from the way the ground loss around the tunnel periphery was modelled as an elliptical shape. Therefore, the indication is that the modified method can be used for the prediction of ground surface settlement induced by tunnelling in sandy soil.

As the K value varies for different soils, calibration of the dimension of the elliptical shape can be realised by means of parametric studies to obtain suitable major and minor axes.

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