Revisit of the Surface Surcharge Effect on the Structural Responses of Shield Tunnel in Spatially Varied Soils

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Abstract. Surface surcharge is regarded to be one of the main factors that will cause ground settlement and large convergence of tunnel. Although the impact of surcharge on tunnel deformation has been studied in recent years, few studies have been dedicated to investigate the effect of spatial variability in soil strength on the ground surface settlement and convergence of tunnel. Hence, this study focused on the effect of soil spatial variability on the responses of the ground and tunnel linings by using the random finite difference analysis. Random fields are generated and mapped into finite difference analysis to reveal the impact of the variation of soil elastic modulus. The influence of the load thickness of soil and distance from load position to the centerline of the tunnel are discussed. The effect of coefficient of variation (COV) of soil's elastic modulus on surface settlement and tunnel convergence is also investigated. The results indicate that ignoring the spatial variability of soil strength will lead to a lower value of the surface settlement and tunnel convergence compared to the results from deterministic analysis. The maximum tunnel convergence value is 30% (15%) larger than deterministic analysis when the COV of soil's elastic modulus is 0.35. The COV of vertical (horizontal) convergence increases with the COV of elastic modulus. The larger the variability of soil leads to a larger change in the tunnel through soil, and resulting in larger convergence changes. Therefore, it is necessary to consider the variability of soil parameters on analyzing the effect of surface surcharge on the settlement and tunnel convergence.

Keywords: Surface surcharge · Surface settlement · Tunnel convergence
Random finite difference method

1 Introduction

At present, urban rail transit plays an important role in public transport system. Shield tunnel is the main structure of urban rail transit. Based on the site investigation and analysis, it is found that the surface surcharge above the tunnel is one of the significant factors that cause the large deformation of the shield tunnel (Wang and Zhang 2013). Shield-driven tunnel construction typically involves excavation in subsurface regions with spatially variable soil. Under such uncertain soil conditions, it is difficult to obtain accurate soil information in advance, for example, the elastic modulus, E_s, and Poisson's ratio, v_s, i.e., the most significant properties for the deformation of shield tunnel.

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Without accurate soil parameters' information, conventional analysis thinks these parameters are same in every layer. But in fact, the soil is anisotropic. Thus, it seems that employing random field analysis approach that are able to incorporate soil uncertainties in analyzing the surface settlement and convergence of tunnel under surface surcharge in spatially variable soil is a more sensible analysis.

In the past, a considerable amount of effort has been devoted to analyzing the influence of surface surcharge on shield tunnel. For instance, WANG analyzed the evolution of transverse deformation of the tunnels under surcharge (Wang and Zhang 2013); ZHANG analyzed the influence of the compressibility of soil layers across by tunnel and soil layers overlaying on tunnel structure deformation and surrounding soil pressure under surface surcharge (Zhang et al. 2016). DAI got the effect of load position on tunnel that the impact is weakened when the deviation distance increased to a certain value (in this case 20 m) (Dai et al. 2006). LI did a study on random finite element method for spudcan foundations in spatially variable soils (Li et al. 2016). However, there has been relatively little effort spent in analyzing the spatial variability of soil on the ground settlement and structural behaviors. Therefore, the analysis of the effect of spatial variability of soil properties on tunnel convergence under surface surcharge are quite necessary.

Therefore, the present study will focus on the surface settlement and convergence of shield tunnel under surface surcharge in spatially variable soil. In this study, only the elastic modulus E_s is considered to be a spatially random property, as v_s is believed to have a smaller relative spatial variability (Fenton and Griffiths 2005). The random finite difference analysis is used in the present study. Random fields of soil elastic modulus are generated and mapped into finite difference analysis to reveal the effect of COV of elastic modulus on the surface settlement and tunnel convergence in random fields.

2 Deterministic Finite Difference Analysis

2.1 Finite Difference Modelling

In this paper, a shield tunnel with its outside diameter D = 6.2 m, internal diameter 5.5 m, thickness 0.35 m and depth H = 17 m is considered. The shield tunnel exemplifies the common used shield tunnel in Shanghai metro, and is modelled as elastic homogeneous ring to allow structural deformations. In the deterministic analysis, we set the soil parameters to be consistent. The soil of elastic modulus is 25 MPa, Poisson's ratio 0.31, cohesion 27 kPa and density 1800 kg/m3. Figure 1 shows finite difference model and contour of z-displacement under overloading (deformed factor: 50), as well as the maximum convergence in vertical and horizontal direction. The maximum vertical (horizontal) convergence is denoted by $\Delta dv(\Delta Dh)$.

This section adopts numerical analysis to study the deformation rules and deflections of shield tunnels underground heaped load of different positions and magnitudes. Finite difference analyses are performed using the FLAC3D 5.0 software. The excavation of the soil is simulated by using the convergence-confinement method to account for soil deformation or ground loss caused by time and space effect (Mroueh

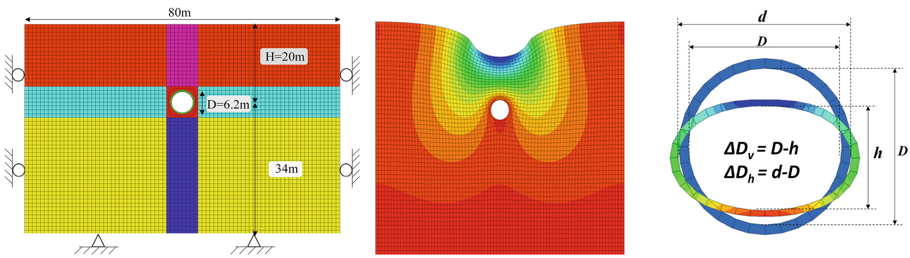

Fig. 1. Finite difference model and the convergence in vertical and horizontal direction of shield tunnel

and Shahrour 2008). The mechanical parameters of the tunnel are shown in Table 1. In the process of simulated the surface surcharge, the loading width is 12 m.

Table 1. Geometric parameters and mechanical parameters of finite element model tunnel

Outside diameter/m	Internal diameter/m	Thickness/m	Elastic modulus/GPa	Poisson's ratio	Density/(kg/m$^{3)}$
6.2	5.5	0.35	34.5	0.2	2500

2.2 Effect of Load Thickness on Surface Settlement and Tunnel Convergence

In this study, we assume that the surface overload is caused by the soil heaped above the tunnel, the surface heap is loaded on a heap of 0.5 m (18 kN/m3) and converted into a uniform load (9 kPa) in the model. In order to get the effect of load thickness on the surface settlement and tunnel convergence, 15 cases with different load thickness are taken into account, as shown in Table 2.

Table 2. Case design on influence of load thickness on the surface settlement and tunnel convergence

Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Load thickness/m	0	0.5	1	1.5	2	2.5	3
Case	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14
Load thickness/m	4	5	6	7	8	9	10

Figure 2(a) shows the variation in the tunnel convergence with the load thickness of soil. In the stage of load thickness is 0–1 m, the incremental value of tunnel convergence increases rapidly with the increase of the load thickness of the soil; in the stage of 1–3 m, the incremental value is basically stable; in the stage of 3–4 m, the incremental value increases rapidly with the increase of the load thickness; and in the

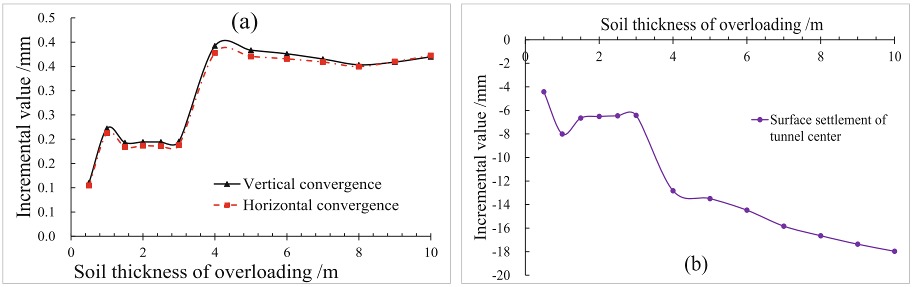

Fig. 2. The effect of load thickness of soil: (a) tunnel convergence; (b) surface settlement of tunnel center

stage of 4–10 m, the incremental value is basically stable. Figure 2(b) shows the variation in the surface settlement of tunnel center with the load thickness. The discipline of the effect is similar to the Fig. 2(a). The load thickness of 3 m the important point that we need pay special attention to.

As shown in Fig. 3, it shows the effect of load thickness of soil on the surface settlement. The incremental value of the surface settlement is relatively small before the thickness is less than 3 m. The incremental value significantly increases when the load thickness of soil lager than 3 m.

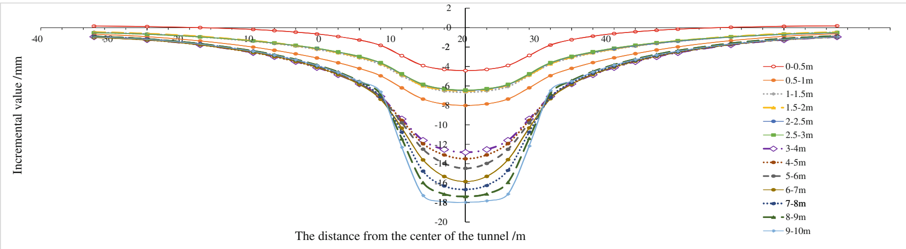

Fig. 3. The effect of load thickness of soil on the surface settlement

To summarize, the 3 m (54 kPa) is a important value that we need pay more attention. In practical engineering, we need to avoid the overloading on the tunnel as far as possible. If we have to be loaded in some emergency special circumstances, the load thickness should not exceed 3 m. Otherwise, the large deformation of tunnel and settlement of surface will occur.

2.3 Effect of the Distance from Load Position to the Centerline of the Tunnel

The location of the overloading is also an important factor. The surface surcharge is not only at the center of the tunnel, so 11 cases with different distance are considered, as shown in Table 3.

Table 3. Case design on influence of deviation distance on the surface settlement and tunnel convergence

Case	1	2	3	4	5	6	7	8	9	10	11
Distance/D	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5

Figure 4a (b) shows the variation in *ΔDv* (*ΔDh*) with the distance from load position to the centerline of the tunnel. It has a noticeable trend that the larger distance, the smaller tunnel convergence. As can be seen from the graph, there has been a rapid decrease when the distance from 0.5D to 3.5D. A gradually stable period occurs while the distance from load position to the centerline of the tunnel lager than 3.5D.

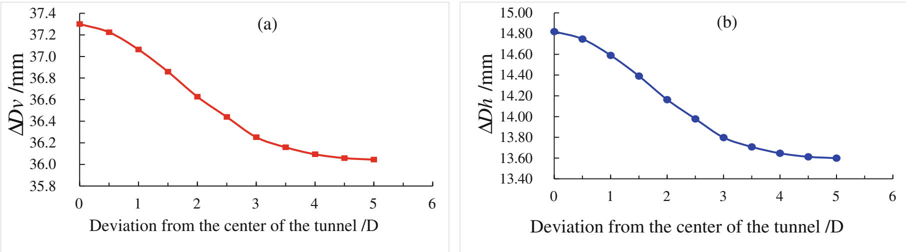

Fig. 4. The effect of distance from load position to the centerline of the tunnel on: (a) *ΔDv*; (b) ΔD_h

Figure 5 shows the variation in surface settlement with the distance from load position to the centerline of the tunnel. It can be concluded from the figure that there has been a great decline in surface settlement with the distance from 0.5D to 3.5D. The settlement remains a slight change when the distance lager than 3.5D. The incremental value curve has something in common with the settlement curve. The incremental value is obviously small and stable when the distance from load position to the centerline of the tunnel lager than 3.5D (in this case). Which is similar to the conclusion of the literature (Yu et al. 2006; Wang et al. 2008), also conforms to the basic principle of

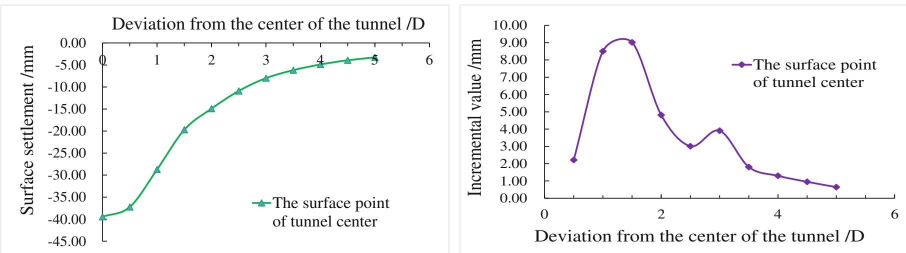

Fig. 5. The effect of the distance from load position to the centerline of the tunnel on the surface settlement

the literature. The farther away the loading position is from the tunnel, the less influence it will have on the tunnel.

In summary, the position of surface surcharge is also a significant factor that we need to consider (Wu 2012). When the distance from load position to the centerline of the tunnel becomes larger, the additional stress of soil around the tunnel becomes smaller, so the effect of tunnel convergence becomes slighter. The impact is rapidly weakening when it becomes from 0.5D to 3.5D. The impact is small while it larger than one particular value. In this case, it is 3.5D. Therefore, we should make the load position as far away from the tunnel as possible to minimize the impact on the tunnel in engineering.

3 Random Finite Difference Analysis (RFDA)

3.1 Random Field Model of Soil's Elastic Modulus

In this section, the model of tunnel also uses the former deterministic model, the load thickness is 3 m (54 kPa). Random fields of elastic modulus are generated using the Karhunen-Loeve expansion. The elastic modulus field is assumed to fit into an exponential covariance function (Huang et al. 2013). The mean value is set as 25 MPa which is consistent with the deterministic analysis, and the scales of COV is shown in Table 4. The COV of Case1 is 0, it was used to compare with other Cases. Other parameters of Case2 to Case7 are exactly same to the deterministic analysis apart from the COV, so that we can get the impact of COV to the tunnel convergence and settlement under the surface loading. For each case, 300 MCS runs are performed for the soil random field and the subsequent finite difference analyses.

Table 4. Scales of COV in anisotropic random fields

Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
COV	0	0.1	0.15	0.2	0.25	0.3	0.35

3.2 Spatial Patterns for Max Settlement and Tunnels Convergence

We pay more attention to the worst case rather than the average in practical engineering. It is bound to have different value of E_S in each region because of the COV of E_s, which will result in different settlement and tunnel convergence. Figure 6 shows the worst spatial pattern which have the maximum value of the surface settlement and tunnel convergence. In Fig. 6, the red regions indicate strong soil and blue regions indicate weak soil. From the Fig. 6(a), we can see that the surface settlement is maximum when the surface center soil is very weak. The most interesting thing is that the maximum arch settlement, ΔD_v and ΔD_h occurs in the same simulation. According to the Fig. 6b, c and d, the soil of tunnel around is so weak that the convergence is very huge. It suggests that the soil of tunnel around play a significant role in the tunnel deformation. The maximum surface (*arch*) settlement is 47.19 *(30.94)* mm, larger than deterministic analysis 21.19 *(17.73)*%. The maximum ΔD_v *(*ΔD_h*)* is 42.77*(19.35)* mm,

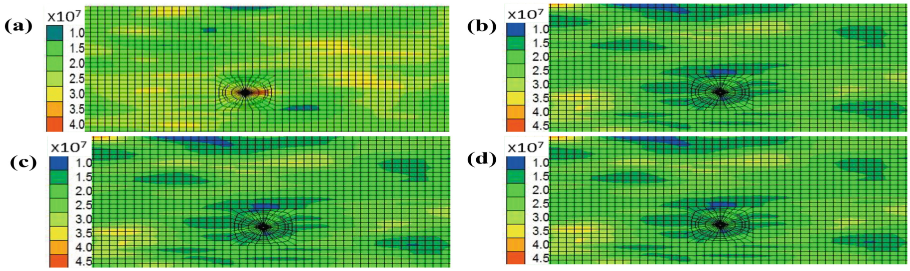

Fig. 6. Realizations with the maximum settlement and convergence for Case7 (COV = 0.35): (a) Maximum surface settlement; (b) Maximum arch settlement; (c) Maximum ΔD_v; (d) Maximum ΔD_h.

larger than deterministic analysis 14.68 *(30.59)%*. It will be disastrous if we design the tunnel using the conventional approach. From another aspect also shows that it is necessary to consider the stratigraphic uncertainty.

3.3 Effect of Elastic Modulus' Variation Coefficient on Surface Settlement

As is demonstrated in Fig. 7(a), we can see clearly that the mean of surface center settlement and arch settlement minor increase with the increase of E_s's COV, but the mean value is basically consistent with the deterministic analysis. However, the maximum settlement value has a considerable increase. From the Fig. 7(b) we can see that the surface center (arch) settlement can lager than deterministic analysis' result. The maximum value is 21.19 (17.73)% larger than deterministic analysis when the COV of E_s reach 0.35. Meanwhile, the percentage of maximum value has a stable increase with the increase of COV which suggests that the bigger E_s's COV, the larger maximum value.

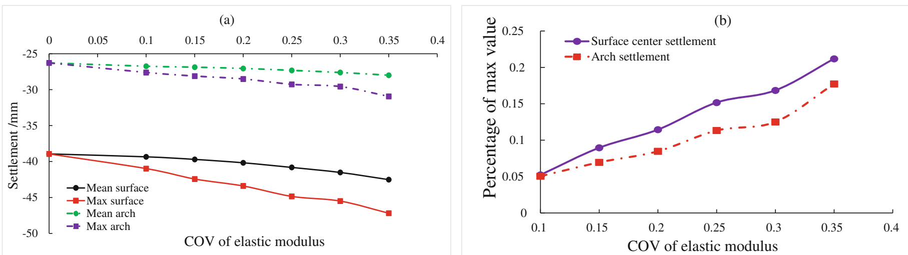

Fig. 7. The impact of COV of E_s on the surface center and arch settlement

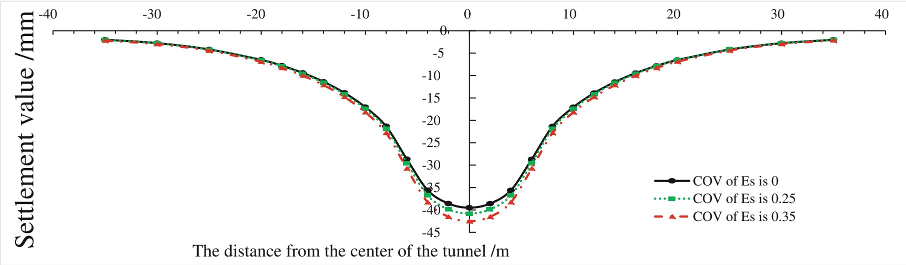

Fig. 8. The effect of COV of E_s on the surface settlement

Figure 8 shows that the change of surface settlement trough with the COV of E_s. In the process of COV from 0 to 0.25 to 0.35, the surface settlement value gradually become large. In a word, the larger the COV value, the greater the spatial variability of the soil. We should pay more attention if the tunnel passes through the soil with large variability of space, otherwise it will have a significant deformation.

3.4 Effect of Elastic Modulus' Variation Coefficient on Tunnel Convergence

Figure 9 shows the variation in the mean and maximum value of ΔD_v and ΔD_h with COV of E_s. The mean value of ΔD_v and ΔD_h is hardly influenced by the COV and keep in line with the deterministic analysis' result. It is clear from the Fig. 9(a) that the maximum value of ΔD_v sharply went up to 42.77 mm while the COV of E_s is 0.35. The value is 14.68% larger than the result of deterministic analysis (37.29 mm). There is not a great deal of difference between ΔD_h and ΔD_v. The maximum value of ΔDh sharply went up to 19.35 mm while the COV of E_s is 0.35. The value is 30.59% greater than the result of deterministic analysis (14.82 mm). The possibility of crossing the weak soil is much greater with the increase of E_s's COV. This is the reason that the maximum value of ΔD_v and ΔD_h is much larger.

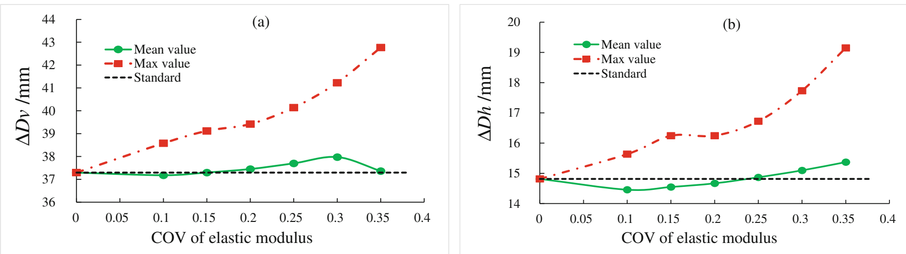

Fig. 9. Mean value of ΔD_v and ΔD_h with COV of elastic modulus

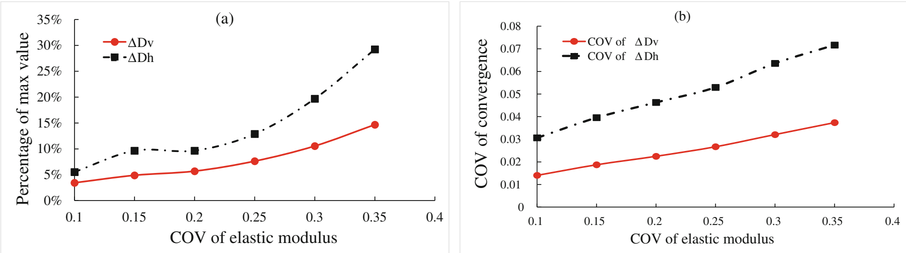

Fig. 10. Variation of convergence statistics with COV of elastic modulus: (a) Percentage of maximum value; (b) COV of *ΔDv* and *ΔDh*

As you can see from the Fig. 10(a), this is a cure graph which describes the trend of the percentage of maximum value of ΔD_v and ΔD_h with COV of elastic modulus. The percentage of maximum value of ΔD_v and ΔD_h was on a steady rise along with the increase of COV of E_s. The percentage of maximum value even reach about 30% (15%) of ΔD_h and ΔD_v. It is very dangerous for the stability of the tunnel. As is indicated in the Fig. 10(b), the higher COV of E_s, the higher COV of ΔD_h and ΔD_v. It suggests that the greater the variability of the soil parameters, the greater the variability of the tunnel convergence. It is easy to understand that the greater the variability of soil, the greater the change in the tunnel through soil, resulting in larger convergence changes. Therefore, a larger factor of safety should be adopted while the tunnel passes through the soil with large spatially variability. At the same time, tunnel reinforcement, grouting and other measures should be used to ensure the stability of the tunnel.

4 Conclusions

This study employs a random finite difference analysis for investigating the variation of settlement and tunnel convergence embedded in spatially varied soils. Random fields are generated and mapped into finite difference analysis to reveal the impact of the variation coefficient of elastic modulus. The effects of the load thickness, the load position and the COV of E_s were investigated. Below some findings from the research in this paper is summarized:

(1) The 3 m (54 kPa) is a important value that we need pay more attention to the load thickness of soil. The incremental value of settlement and tunnel convergence significantly increases when the load thickness lager than 3 m (54 kPa).
(2) The impact on surface settlement and tunnel convergence is rapidly weakening when the distance from load position to the centerline of the tunnel becomes from 0.5D to 3.5D. The impact is small while it larger than one particular value. In this case, it is 3.5D. Therefore, we should make the load position as far away from the tunnel as possible to minimize the impact on the tunnel in engineering.
(3) Ignoring the spatial variability of soil strength leads to a lower value of the surface settlement and tunnel convergence. The percentage of maximum value even reach

about 30% (15%) of ΔD_h and ΔD_v. It is very dangerous for the stability of the tunnel.

(4) The COV of ΔD_h and ΔD_v increases with the COV of E_s. It is suggested that the variability of the tunnel convergence increases with the variability of the soil parameters. That means the larger the variability of soil leads to a larger change in the tunnel through soil, and resulting in larger convergence changes.

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