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# Prediction methods on tunnel-excavation induced surface settlement around adjacent building

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**Abstract.** With the rapid development of urban underground traffic, the study of soil deformation induced by subway tunnel construction and its settlement prediction are gradually of general concern in engineering circles. The law of soil displacement caused by shield tunnel construction of adjacent buildings is analyzed in this paper. The author holds that ground surface settlement based on the Gauss curve or Peck formula induced by tunnel excavation of adjacent buildings is not reasonable. Integrating existing research accomplishments, the paper proposed that surface settlement presents cork distribution curve characters, skewed distribution curve characteristics and normal distribution curve characteristics when the tunnel is respectively under buildings, within the scope of the disturbance and outside the scope of the disturbance. Calculation formulas and parameters on cork distribution curve and skewed distribution curve were put forward. The numerical simulation, experimental comparison and model test analysis show that it is reasonable for surface settlement to present cork distribution curve characters, skewed distribution curve characteristics and normal distribution curve characteristics within a certain range. The research findings can be used to make effective prediction of ground surface settlement caused by tunnel construction of adjacent buildings, and to provide theoretical guidance for the design and shield tunnelling.

**Keywords:** shield tunnel; adjacent structure; surface settlement; cork distribution; skewed

## 1. Introduction

With the fast pace of urbanization in China, it is indispensable to develop underground transportation as a part of the sustainable development in urban. However, ground displacement and structure deformation caused by construction have been widely concerned in the field of the construction of urban subway systems in China, where Peck’s equation has been widely used to predict ground deformation. Peck (1969) proposed an empirical formula by which the surface settlement obeys the normal distribution during the stage of tunnel construction, based on observation of the shape of settlement trough on the surface of the tunnel as well as abundant measured data. However, Peck’s equation did not consider the existence of structures. Peck’s equation can still be found in studies by most scholars on the coactions of tunnel-structure-ground for the purpose analysis (Mathew and Lehane 2013, Do *et al*. 2014, Zymnis *et al*. 2013, Mroueh and Shahrour 2003, Jenck and Dias 2004, Qi 2012). Ding held that neglecting the self-weight of structure would cause significant discrepancies of surface settlement and width of settlement

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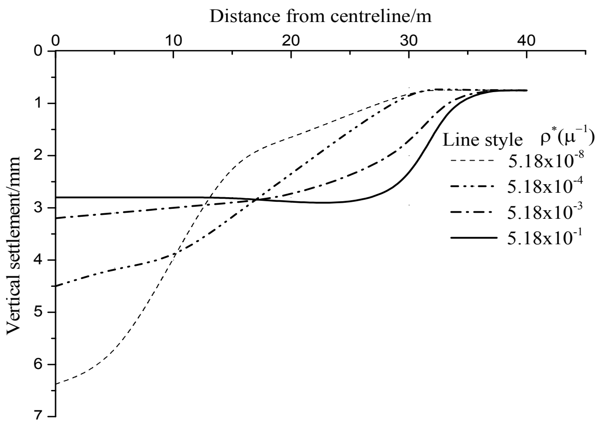


Fig. 1 Settlement profile of structure with different relative bending stiffness

trough resulted by the excavation of tunnel (Ding *et al*. 2012).

In this case, Han (Han *et al*. 2007) improved Peck's equation and adopted Gaussian curve based on the width of settlement trough to fit the actual settlement curve. However, Han used a relatively large value for the width of settlement trough and the value was much larger than the recommended value of natural clay ground surface in London. The paper considered that Han did not discover the fact that the settlement curve of adjacent structures caused by the construction of tunnel can appear to be skewed distribution, so such a value failed to reflect precisely the pattern of surface settlement caused by the construction of tunnel.

Meanwhile, when the tunnel penetrates the area under the structure, the settlement curve is significantly different from the curve predicted by Peck's equation. The shape of settlement curve is not like a funnel as in normal distribution but a bottle cork that is axisymmetric. For example, Potts *et al*. (Potts and Addenbrooke 1997) proposed a 'related stiffness method' based on numerical plane finite element analysis. By this method, the settlement curve is normally distributed when the stiffness is zero and is a cork-shaped curve (refer to Fig. 1) when the stiffness increases.

In addition to the fact that the stiffness of structure confines the size of the displacement of ground, the distance between the tunnel and structure affects the distribution of settlement curve. Based on the existing research (Wei 2008), this study proposed a concept that the settlement curve will be either cork-shape distribution or skewed distribution: (1) When the excavating area is under the structure, the settlement curve appears to be cork-shape distribution within the range of the length of the structure. (2) When excavating area is around the area of the structure (the ratio of the horizontal distance between the axis of the structure and the axis of the tunnel $L$ to the outer diameter of tunnel shield $D$ approximately ranged from 0.5 to 3), the settlement curve is skewed distribution curve. (3) When the excavation is away from the structure by a certain distance ($L/D \geq 3$), the settlement curve will be normal distribution curve as predicted by Peck's equation.

## 2. Cork-shape distribution curves

### *2.1 Predicting equations and selection of parameters for cork-shape distribution curves*

The stiffness of the structure confines the deformation of the ground. For structure with stiffness which is evenly distributed, the confining effect is even and continuous, and thus the resulting deformation curve of structure is also continuous curve and the location of maximum settlement point do not change (in practical engineering it can be deemed approximately unchanged) (Han 2006). When tunnelling the area underneath the structure, the deformation of the foundation due to confinement becomes more homogeneous, as represented by a smoother settlement trough. Therefore, the deformation curve swifts from funnel-shape as in the case of normal distribution to cork-shape.

Celestino *et al.* (2000) considered the error when matching with Peck's equation based on measured data, and proposed the following predicting equation

$$S = S_{\max} \frac{1}{1 + \left( \frac{|x|}{a} \right)^b} \tag{1}$$

In which $S$ is the predicting equation, $S_{\max}$ is the maximum settlement in transverse direction, $x$ is the distance between the settlement-calculating point and the centre of axis of the structure, $a$ is a constant (dimension in length) influencing width of settlement trough, $b$ is a constant larger than 1 (dimensionless) to affect the shape of the settlement trough.

This study agrees that the above equation can better describe the 'cork-shape curve', and is capable of predicting the ground displacement when the tunnel penetrates the area underneath the structure. The values of $a$ and $b$ can be determined using the following rules in this paper:

When $x$ is less than or equal to half of the width of the foundation $B$, $a/D = 0.8(z_0/D) + 0.5$; When the distance between the settlement point to be calculated and the centre of axis of the structure $x$ is larger than half of the width of the foundation $B$, $a/D = 0.46(z_0/D) + 0.42$. The value of parameter $b$ ranges from 2 to 3 and is related to the form of the foundation, width of the structure. For normal block foundation, the maximum value is suggested.

Two numerical analytical examples are used in this study to validate the predicting equation.

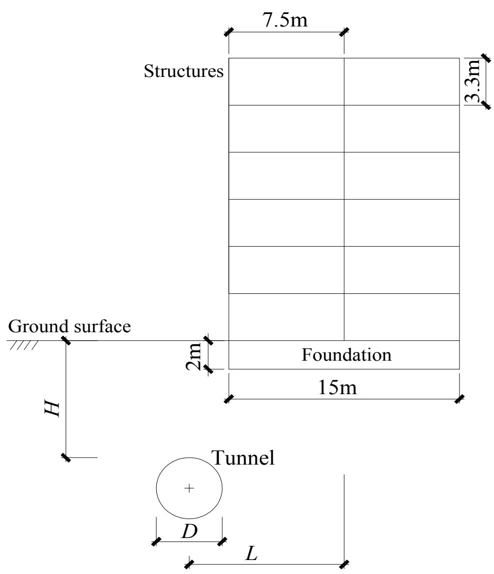


Fig. 2 The geometric relationship of buildings and tunnel

### *2.2 Numerical example validation No. 1*

Ding *et al*. (2009) established numerical model of a subway tunnel in different conditions of foundation structure by using ANSYS. The dimensions of the tunnel and structure are shown in Fig. 2. In Fig. 2, $H$ is the depth of ground cover of the tunnel (m); $L$ is the horizontal distance between the axis of the structure and the axis of the tunnel (m); $D$ is the outer diameter of the tunnel shield (m).

The foundation of the structure was block foundation with burial depth of 2 m and length of 15 m. The foundation adopted C20 concrete with an elastic modulus of 25.5 GPa, a Poisson's ratio of 0.2 and a density of 2.5 g/cm$^3$. The dimensions are shown in Fig. 2. Within the whole model,

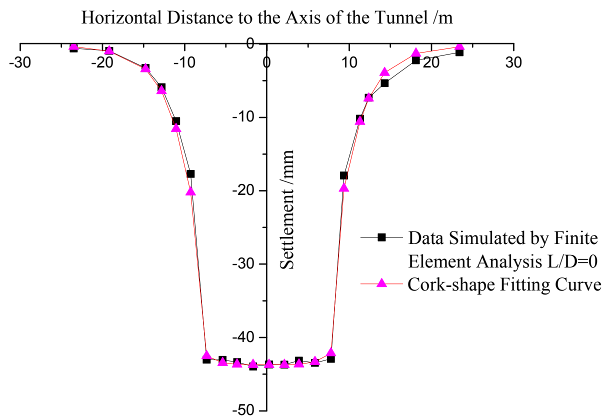


Fig. 3 Fitting chart of surface settlement induced by tunnel excavation (tunnel under buildings)

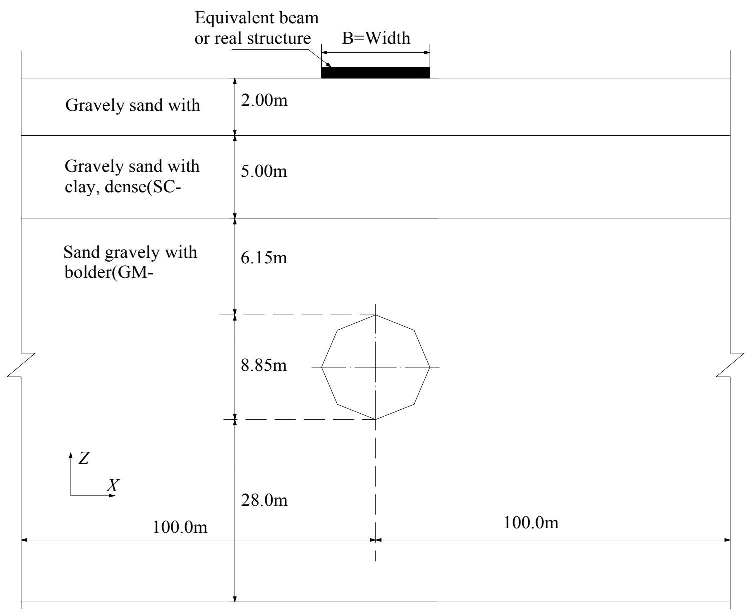


Fig. 4 The geometric relationship of buildings and tunnel

100 m was taken in horizontal direction and 40 m in vertical direction. The burial depth of the tunnel was 5.0 m and the outer diameter of the tunnel shield was 6 m.

It can be seen from Fig. 3 that due to the existence of stiffness of the structure, results calculated by finite element method was significantly different from normal distribution calculated by Peck's equation. Although the curve was axisymmetric, ground settlement showed overall settle due to the confinement of structure. When fitted using cork-shape curve as shown in Fig. 3, the shape of settlement trough and width matched favourably. However, due to the fact that the foundation of the structure was block foundation, parameter *b* was taken as the maximum value of 3.

### 2.3 Numerical example validation No. 2

Maleki *et al*. (2011) analyzed the interaction of tunnel and adjacent building by using 3D finite element software PLAXIS 3D and considered the fact that the numbers of levels of the buildings were different, then the structure was simplified into equivalent beam. The dimensions of the tunnel and structure were shown in Fig. 4. The burial depth of the tunnel was 13.15 m, and the tunnel penetrated the area underneath the structure. The relevant physical parameters of the structure, tunnel and ground can be found in detail in Maleki's paper.

It can be seen from Fig. 5 that the ground settlement caused by the excavation of tunnel underneath the structure basically matched 'cork-shape distribution', and the curve reflected favourably the effect of the existence of the structure on the displacement caused by tunnelling underneath the structure. In the fitting curve in Fig. 5, parameter *b* was taken as 2. Compared with Fig. 3, the width of settlement trough and the width of the structure matched favourably, but there were discrepancies in the shape of distribution of settlement, which was mainly due to the fact that reference (Ding *et al*. 2009) incorporated block foundation. Normally, the values of *a* and *b* are related to the burial depth of the tunnel, the width, numbers of layers and stiffness of the structure as well as the softness of the ground. For structure with larger width, the value of b can be taken smaller but when the width is smaller, the value of *b* should be taken larger; when taken the value of *b* in respect to the softness and quality of the ground, the value of *b* can be taken larger when the ground is softer.

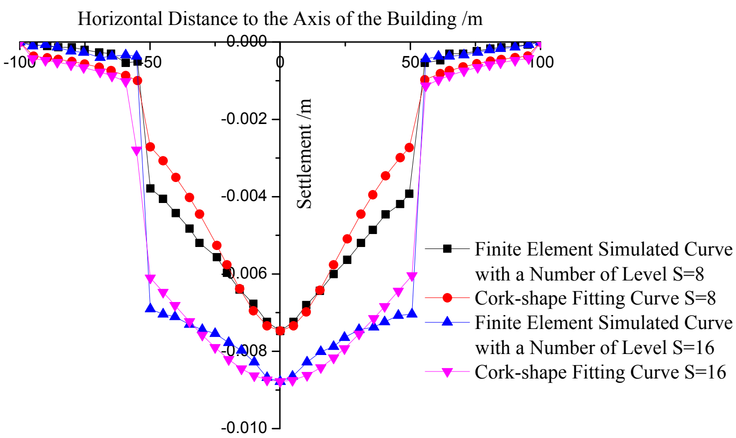


Fig. 5 Fitting chart of surface settlement induced by tunnel excavation under buildings with different layers

## 3. Skewed distribution curve

### *3.1 Prediction curve and selection of parameters for skewed distribution curve*

Because most subway tunnels do not penetrate the area directly underneath the structure, cork-shape curve is not able to fit completely the relevant settlement curve. This study proposed that in a certain range, there is an influential area for the structure and tunnel. Within such influential area, the distribution of settlement curve does not comply with normal distribution.

When the tunnel does not excavate the area directly underneath the structure but within the influential area (the ratio of the horizontal distance between the axis of the structure and the axis of the tunnel $L$ to the outer diameter of tunnel shield $D$ ranged from 0.5 to 3), ground settlement will still increase and the structure may incline or even crack. In this situation, the distribution of settlement curve is neither normal distribution nor cork-shape distribution, but ‘skewed distribution’.

The following equations to predict the skewed distribution curve are proposed in this paper:

When the tunnel locates at the left side of the central axis of the structure

$$S(x) = S_{\max} \cdot e^{\frac{-\left[\ln \frac{x+\alpha \cdot B}{2L}\right]^2}{2w^2}} \tag{2}$$

When the tunnel locates at the right side of the central axis of the structure

$$S(x) = S_{\max} \cdot e^{\frac{-\left[\ln \frac{-x+\alpha \cdot B}{2L}\right]^2}{2w^2}} \tag{3}$$

In which: $S_{\max}$ is the maximum transverse ground settlement; $S(x)$ is the ground settlement distributed along transverse $x$ direction, $x$ is the horizontal distance from settlement points to the center of tunnel, m; $B$ is building horizontal length, m; $L$ is the eccentricity measured as the distance between the centre of the tunnel and the centre of the structure, with unit in metre; $w$ is the empirical factor taken from 0.60 to 0.70 according to ground quality; $\alpha$ is a scale factor taken from 0.8 to 1.0 according to the basic form of foundation of the structure.

To validate the above predicting equations, the equations for skewed distribution curve were used to fit the established research results and the results from the fitting proved the viability of the skewed distribution curve.

### *3.2 Numerical example validation No. 3*

The numerical calculation model and calculated settlement results from reference (Ding *et al.* 2009) were used in example No. 1. $w$ was taken according to the ground quality as 0.6 and $\alpha$ was taken as 1.0 according to the form of foundation used in the structure. It can be seemed from Fig. 6 that when $L/D$ = 0.5 to 1, the difference of settlement between the front and back of the structure was significant, and the ground settlement above the tunnel diverged obviously from normal distribution, forming a large funnel shape settlement area in the centre. The structure inclined notably and the settlement curve matched with skewed distribution curve, being a better fitting result. Based on the aforementioned discussion in this study, there is a certain range for the

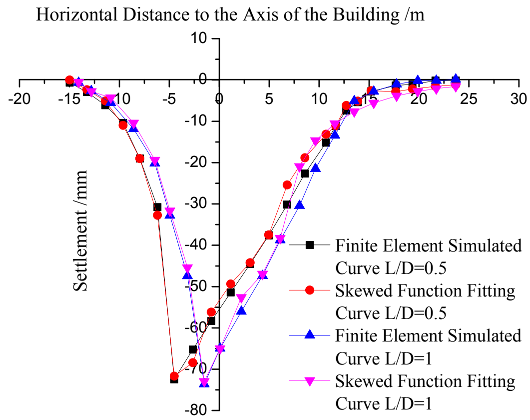


Fig. 6 Fitting chart of surface settlement induced by tunnel excavation under buildings with mass-type foundation

existence of skewed distribution curve. When $L/D \geq 3$, the ground settlement curve still obeys normal distribution, and the discrepancy of settlement between the front and back of the structure is negligible. The existence of the structure does not affect significantly the excavation of the tunnel.

### 3.3 Numerical example validation No. 4

Han (Han *et al.* 2007) collected abundant measured settlement data from adjacent buildings from the JLE subway project in England when analyzing the pattern of settlement curve caused by the excavation of subway. However, he used Gauss curve to fit the data and proposed that there was not much effect of the distance between the structure and tunnel, which was obviously different from actual situation. Because the settlement curve of adjacent structures caused by tunnelling appears to be skewed distribution has not been discovered, the value from fitting could not reflect accurately the distribution form of ground settlement. In this study, a measured settle-

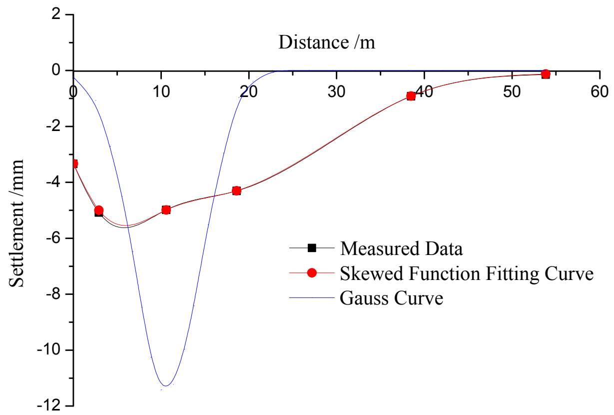


Fig. 7 Fitting chart of surface settlement induced by London mayor residence tunnel excavation

ment curve was taken at the nearby of Mansion House and fitted with the curve calculated by Eq. (3), as shown in Fig. 7. The $w$ was taken according to the ground quality as 0.6 and $\alpha$ as 1.0 according to the form of foundation used in the structure. The calculated results matched favorably with the measured data which proved further the viability of the prediction by skewed distribution curve.

It can be seen from the measured settlement curves in Figs. 7 and 8 that ground settlement of the adjacent structures caused by tunnelling normally appeared to be skewed distribution. Only when excavating area is out of the influential range, will the settlement comply with Peck's normal distribution. The width of settlement trough and the shape of the skewed distribution curve can be affected by factors such as the distance of adjacent structure, the stiffness and the ground quality. It is therefore clear that when studying the distribution of settlement of adjacent structures caused by subway tunnelling, the interaction between ground, tunnel and structure must be considered.

### *3.4 Numerical example validation No. 5*

Shahin *et al*. (2006) established a centrifuge model experiment to study ground settlement of

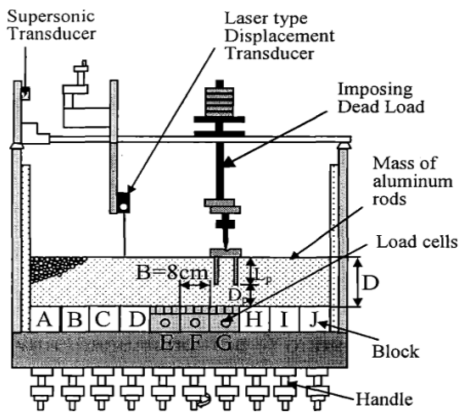


Fig. 8 Excavation scheme of the tunnel adjacent to buildings in centrifuge experimental simulation

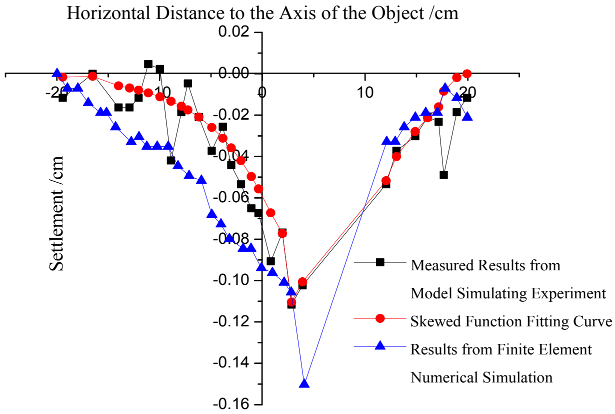


Fig. 9 Fitting chart of surface settlement in centrifuge experimental simulation

adjacent structure caused by tunnelling (as shown in Fig. 8), and conducted 2D numerical simulation to compare and analyze. In the study, $D$ is the burial depth of the tunnel; $B$ is the excavating distance of tunnel shield; $L_P$ is the burial depth of the foundation of the structure. All relevant parameters can be found in this reference. Fig. 9 respectively shows the settlement curves based on the data from the model experiment, the curve analyzed by finite element and the curve fitted by using Eq. (3).

It can be seen from Fig. 9 that the predicted skewed distribution curve matched favorably with the results from finite element method and model experiment. $w$ was taken according to the ground quality as 0.6 and $\alpha$ was taken as 1.0 according to the form of foundation used in the structure. However, compared with the predicted results from Fig. 7, the discrepancy was significant, which was likely due to the fact that the form of foundation of the structure was pile foundation. Although the settlement curve was skewed distribution, the smoothness of the curve was poor. Nevertheless, the founding accorded with the previous studies that the influence of pile foundation on the distribution curve of ground settlement is slightly different from independent foundation and block foundation.

## 4. Conclusions

Subjected to the comparison and analysis of the existing research, the author expanded further about the distribution of ground settlement of adjacent building caused by tunnelling. Some creative conclusions were consequent upon previous study.

- Ground settlement based on Gauss curve or Peck's equation was deemed inappropriate to adjacent building caused by tunnelling. The paper points out that the interaction between the ground, tunnel and structure must be considered, when studying ground settlement of adjacent building caused by tunnelling.
- The paper defined three settlement curves that applies to different situations: when excavating the area underneath the structure, within the distorting range and outside the distorting range, ground settlement appears to be respectively cork-shape curve, skewed distribution curve and normal distribution curve.
- Calculating equation and value range of relevant parameters of cork-shaped distribution and skewed distribution were proposed.
- Through fitting analysis and comparative study of relative value simulation, actual measurement and model experiment, in the paper, the effectiveness and viability of the cork-shaped curve prediction as well as skewed distribution prediction to ground settlement prediction was proved.

This study provides complete and reliable predicting method of ground settlement of adjacent structure caused by tunnelling. It is of great significance to protect the surrounding environment and structure of the tunnel. The soil settlement induced by adjacent buildings shield tunnel excavation runs throughout in the tunnel construction. In addition to the soil, the settlement is also influenced by the buried depth of tunnel, groundwater level, grouting, the distance between tunnel and buildings, the stiffness of buildings, foundation forms, and so on. The ground settlement affected areas and degrees caused by these factors, remains to be further in-depth study, and it can be a major direction for future work.

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