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Publication date
2016

Document Version
Accepted author manuscript

Published in
Proceedings of the 2016 World Tunneling Congress

Citation (APA)
Vu, M. N., Broere, W., & Bosch, J. (2016). Effects of cover depth on ground movements induced by shallow tunnelling. In *Proceedings of the 2016 World Tunneling Congress* Society for mining, metallurgy & exploration.

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Effects of Cover Depth on Ground Movements Induced by Shallow Tunnelling

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INTRODUCTION

Shield tunnelling is often used in constructing underground infrastructure in cities due to the ability to limit settlements and damage to existing buildings. However, in an urban environment with soft overburden and buildings on pile foundations such as the North-South Line project in Amsterdam, there is a tendency to design the tunnel well below the surface and below the pile tip level in order to reduce interaction between tunnelling process and piles. This results in deep tunnels and deep station boxes. When the tunnels are located close to the surface and above the pile tip level, this would reduce the required depth of the station boxes and the construction cost. Moreover, other benefits of shallow tunnels are the low operational cost in the long-term and shorter traveling time from the surface to the platforms. Still, the tunnels should be constructed in such a manner that existing buildings are not structurally damaged, which results in a minimum required distance between tunnelling process and existing buildings. In this paper, the extent of the area that is influenced by tunnelling will be investigated in order to determine the limit distance from tunnelling to existing foundations without inducing too large building deformation.

From analysing empirical data of many shield tunnels, Peck (1969) firstly presented the settlement trough on the surface induced by tunnelling in soft soil as a Gaussian distribution. This is also confirmed by other authors (Cording and Hansmire, 1975; Mair et al., 1993; Ahmed and Iskander, 2010). In this study, the Gaussian curve is used to investigate the ground movement when tunnelling in order to find the effects on existing structures.

Based on the results from centrifuge test and empirical data, Mair et al. (1993) showed that the subsurface settlement profile distributes as the Gaussian curve also. The width of settlement trough at the depth z depends on the depth of the tunnel z_0 and a coefficient K depending on depth. Other studies by Moh et al. (1996), Grant and Taylor (2000) and Jacobsz (2003) based on Mair et al. (1993) proposed a limited change of K in various kinds of soil.

Assessing the impact of underground construction on existing structures in urban area is important in design. Many studies have focused on the ground movements around tunnelling and the settlement trough on the surface but research focused on the ground movements that affect nearby buildings for a first assessment the stability of the buildings and the effect of tunnelling near existing deep foundation has only recently gained interest in geotechnical studies. The affected area due to tunnelling should be estimated in order to avoid the impact on the existing foundations. The responses of building due to

Table 1: Typical values of maximum building slope and settlement for damage risk assessment (Rankin, 1988)

Risk Category	Maximum slope of building	Maximum settlement of building (mm)	Description of risk
1	Less than 1/500	Less than 10	Negligible; superficial damage unlikely
2	1/500 - 1/200	10-50	Slight; possible superficial damage which is unlikely to have structural significance
3	1/200 - 1/50	50-75	Moderate; expected superficial damage and possible structural damage to buildings, possible damage to relatively rigid pipelines
4	Greater than 1/50	Greater than 75	High; expected structural damage to buildings. Expected damage to rigid pipelines, possible damage to other pipelines

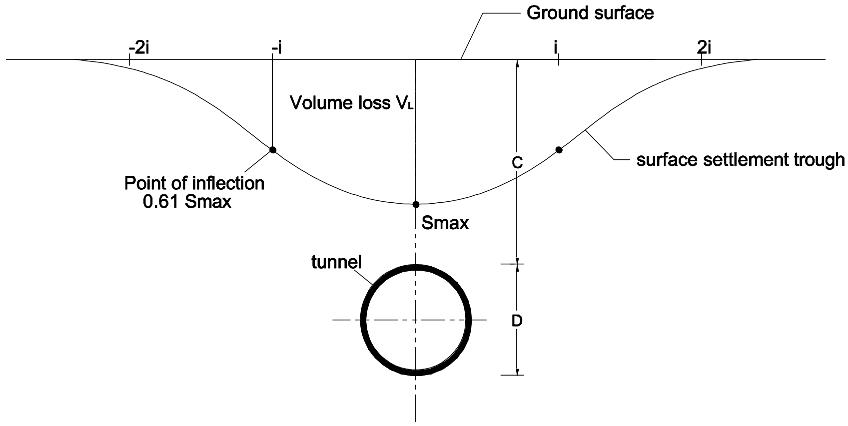


Figure 1. Transverse settlement trough due to tunnelling (Peck, 1969)

tunnelling have been investigated by many authors (Rankin, 1988; Boscardin and Cording, 1989; Mair et al., 1996; Franzius, 2004; Giardina, 2013). From these, the Limiting Tensile Strain Method proposed by Boscardin and Cording (1989) has been widely used in design. This method has four steps: predicting the greenfield movement; projection of greenfield ground movement on the building; determination of induced building strains and classification of damage related to strain levels. Table 1 shows the value of maximum slope and settlement for the building with a category damage risk assessment proposed by Rankin (1988).

In this study, the value for category 1 which is the lowest damage category is used, setting the maximum slope ω_{max}=1/500 and maximum settlement of building u_{max}=10mm. The influence of building stiffness and the difference between sagging and hogging zones of the settlement trough in this risk assessment is not taken into account in this paper. This paper takes a look at the ground movements both at the surface and subsurface when tunnelling in soft soils with deep foundations in order to define the areas where ground movements remain below the acceptable limits for the buildings and to estimate the effect of C/D on the extent of this limited ground movement area.

EFFECT OF C/D ON SURFACE SETTLEMENT

The transverse settlement shape of the ground surface shown in Figure 1 as a Gaussian distribution (Peck, 1969) can be estimated from the maximum settlement $S_{v,max}$ at the surface directly above the tunnel location and the trough width i as follows:

$$s_v = S_{v,max} exp\left(\frac{-x^2}{2i^2}\right) \tag{1}$$

The volume loss can be estimated by:

$$V_s = \sqrt{2\pi} i S_{v,max} \approx 2.5 i S_{v,max} \tag{2}$$

where V_s is the volume of settlement trough per unit tunnel length.

For a circular tunnel, V_s is often calculated via the volume loss V_L as the percentage of the notional excavated tunnel volume (Mair et al., 1993):

$$V_s = V_L \frac{\pi D^2}{4} \tag{3}$$

The volume loss around tunnel includes loss volumes caused by deformations due to face support, passage of the tunnelling machine and the annular gap grouting (Maidl, 2012). According to Cording and Hansmire (1975), when tunnelling in drained conditions, V_s is less than the volume loss around the tunnel due to dilation and when tunnelling in undrained conditions, V_s equals volume loss around the tunnel. In calculation, V_s is often assumed equal to the volume loss around the tunnel.

The shape of curve is determined by the position of the inflection point i. The width of the settlement trough depends on the depth of the tunnel and the soil parameters. O'Reilly and New (1982) gave the relationship:

For cohesive soils: $$i = 0.43 z_0 + 1.1 \tag{4}$$

and for granular soils: $$i = 0.28 z_0 - 0.1 \tag{5}$$

This relationship was also compared by Mair and Taylor (1999) to the relations for settlement trough width and depth of tunnel axis from many authors and recommended for practical purposes.

From Equations 2 and 3, the maximum transverse settlement can be calculated as:

$$S_{v,max} = \sqrt{\frac{\pi}{2}} \frac{V_L D^2}{4i} \tag{6}$$

Therefore, the transverse settlement trough can be described as:

$$s_v = \sqrt{\frac{\pi}{2}} \frac{V_L D^2}{4i} exp\left(\frac{-x^2}{2i^2}\right) \tag{7}$$

The horizontal component of the settlement can damage buildings on the surface when tunnels are constructed in the urban area. O'Reilly and New (1982) propose the following to estimate the horizontal displacement for tunnelling in clays:

$$s_h = s_v \frac{x}{z_0} \tag{8}$$

Another important assessment in tunnelling design is the slope, which can be estimated as the first derivative of the settlement trough as:

$$\omega \approx tan\omega = s_v' = -\frac{S_{v,max}}{i^2} x exp\left(\frac{-x^2}{2i^2}\right) = \sqrt{\frac{\pi}{2}} \frac{V_L D^2}{4i^3} x exp\left(\frac{-x^2}{2i^2}\right) \tag{9}$$

Figure 2 presents the relationship between maximum settlement $S_{v,max}$ with C/D ratio in cohesive and granular soil for a tunnel with diameter D=6m and V_L = 0.5%. This figure shows that the deeper the tunnel is, the smaller the maximum settlement $S_{v,max}$ at surface is. From Equations 4 and 5, it then follows that settlements are spread over a larger surface area for a fixed volume loss.

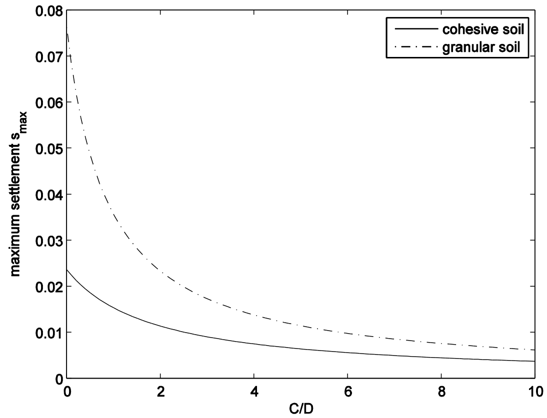


Figure 2. Relationship between $S_{v,max}$ and C/D with tunnel diameter D = 6m

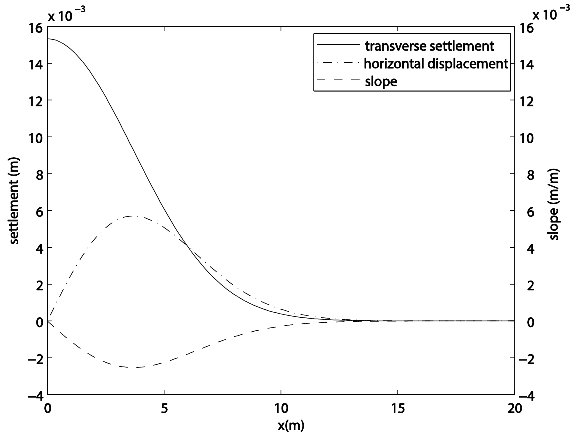


Figure 3. Surface settlements and slope due to tunnelling with diameter D = 6m and C/D = 0

Figure 3 shows the transverse settlement, horizontal displacement and the slope on the surface in the case of tunnel with diameter D=6m, at the depth z_0=6m or C/D=0.5 in cohesive soil. This figure agrees with the conclusion from Mair and Taylor (1999) that $S_{h,max}$ occurs at the position of the inflection points of the settlement trough. And as expected, the maximum slope of surface settlement appears at the position of inflection points of the settlement trough.

In designing a tunnel under existing structures, it is necessary to determine the extent to which the building is influenced by the tunnel. The theoretical influence zone is often presented via the distance from the surface building to the tunnel axis. In this study, the relationship between C/D ratio and this distance is estimated when the surface settlement reaches the allowable settlement u_{max} =10mm and allowable slope ω_{max} = 1/500 corresponding with the risk category 1 in table 1. Figure 4 illustrates this problem. The relation between the maximum allowable settlement u_{max} and the horizontal distance to the tunnel centre line x is given by:

$$u_{max} = S_{v,max} exp\left(\frac{-x^2}{2i^2}\right) = \sqrt{\frac{\pi}{2}}\frac{V_L D^2}{4i} exp\left(\frac{-x^2}{2i^2}\right) \quad (10)$$

The distance x from the building to tunnel axis corresponding with settlement u_{max} is:

$$x = \sqrt{-2i^2 ln\left(\frac{u_{max}}{S_{v,max}}\right)} = \sqrt{-2i^2 ln\left(\frac{u_{max} i 4\sqrt{2}}{V_L D^2 \sqrt{\pi}}\right)} \quad (11)$$

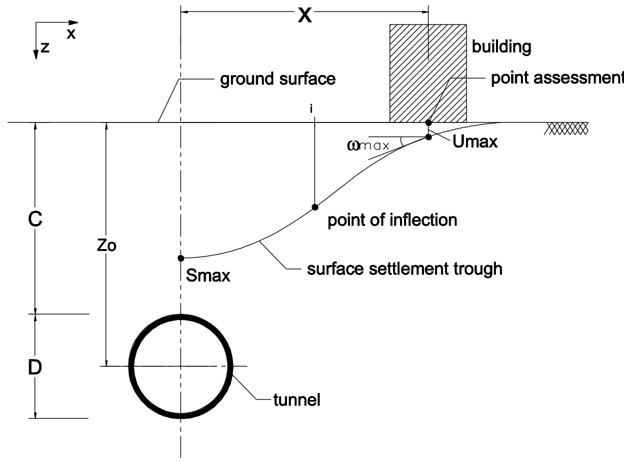


Figure 4. Geometry of a tunnel and existing surface building in a preliminary settlement analysis

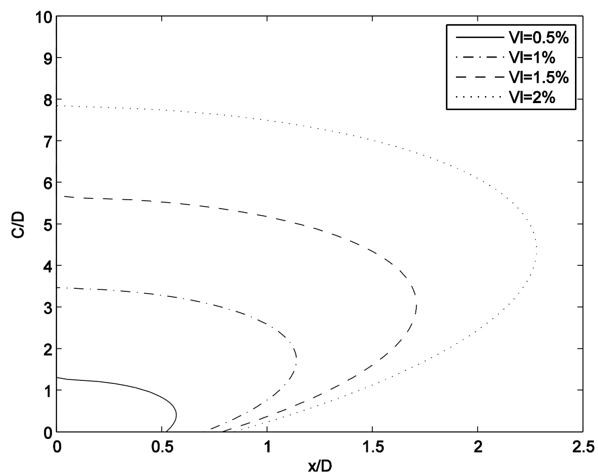


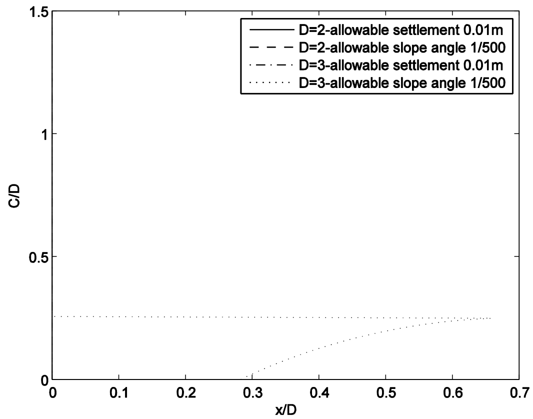
Figure 5. Relationship between x/D and C/D ratios in the case of tunnel with D = 6m in cohesive soil and the allowable settlement u_{max} = 10mm

Figure 5 shows the relationship between x/D and C/D ratios for the case of a tunnel with diameter D=6m in cohesive soil for various volume loss V_L with the allowable settlement u_{max} =10mm. The area inside the curve represents the zone where allowable settlements are exceeded and the tunnel is too close to the building. This unsafe area is also determined for particular values of V_L. This figure indicates that for larger volume loss, larger distances x and C/D ratios are required. With C/D and x/D inside the unsafe area for volume loss V_L=0.5%, the surface settlement is larger than u_{max}. On the boundary of this area, the surface settlement equals u_{max}. In the case of V_L = 0.5%, it also shows that with C/D ratio more than 1.25 the surface settlement is always less than u_{max}. With x/D from 0.522 to 0.57 or x from 3.1 to 3.4m there are two values of C/D ratio or two depths of the tunnel that the settlement of the building equals u_{max}. With x/D more than 0.574 or x larger than 3.4m, the surface settlement is always less than u_{max} again. When the slope is considered with ω_{max} = 1/500, the following equation is derived from Equation 9 :

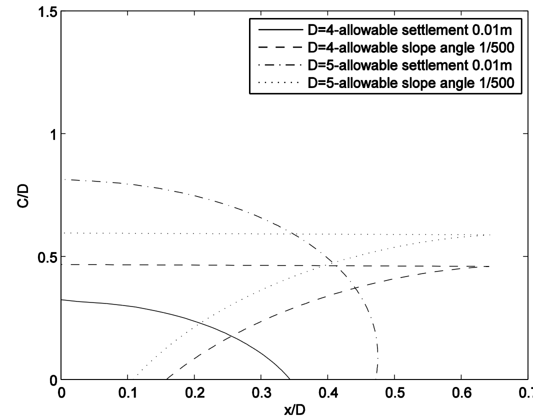
$$\omega_{max} = -\frac{S_{v,max}}{i^2} xexp\left(\frac{-x^2}{2i^2}\right) \quad (12)$$

Table 2: Diameter D_0 value

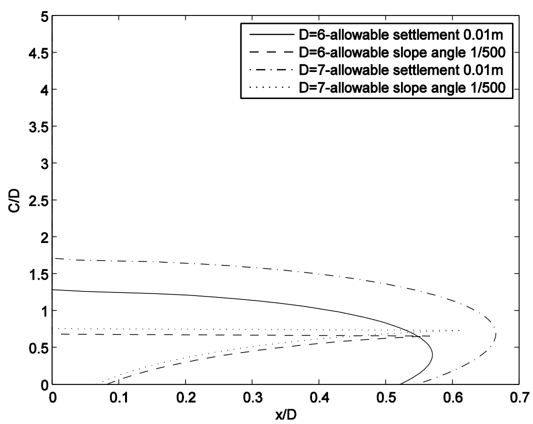
Volume loss V_L(%)	Diameter D_0(m)	
	Cohesive soil	Granular soil
0.05	17.7	8.15
0.01	10.28	3.58
0.015	7.64	1.79
0.02	6.24	0
0.5	3.42	0
1	2.25	0
2	1.51	0



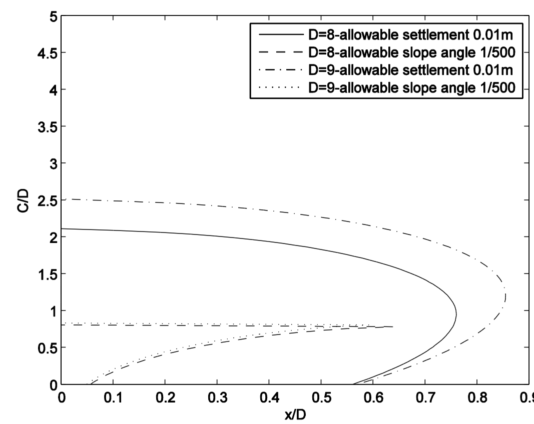
(a) D= 2 and 3m



(b) D= 4 and 5m



(c) D= 6 and 7m



(d) D= 8 and 9m

Figure 6. Relation between x/D and C/D with various tunnel diameter D in cohesive soil and V_L = 0.5%

The distance x from the building to tunnel axis corresponding with slope ω_{max}=1/500 is :

$$x = \frac{\omega_{max} i^2}{S_{v,max}\sqrt{-\dfrac{\omega_{max}^2 i^2}{S_{v,max}^2 LambertW\left(-\dfrac{\omega_{max}^2 i^2}{S_{v,max}^2}\right)}}} \tag{13}$$

where the LambertW function W(x) is a set of solutions of the equation x = W(x) expW(x).

Figure 6 shows the relationship between x/D and C/D in the case of a tunnel in cohesive soil with allowable settlement of the building u_{max} = 10mm and the allowable slope ω_{max} = 1/500 and V_L = 0.5% for various D. From this figure, it can be seen that the smaller the tunnel diameter D is, the smaller the unsafe area due to maximum settlement u_{max} is for a given volume loss V_L. In this case when the diameter D=2 and 3m, the unsafe settlement area disappears altogether. Therefore, there exists a value of D that $S_{v,max} \leq u_{max}$ for any values of x and C. The settlement is maximum at the location directly above the tunnel axis x=0 and solving Equation 6 for $S_{v,max} = u_{max}$ yields the diameter D_0 where the maximum settlement is always less than u_{max}, irregardless of the cover. This only occurs for tunnels at the diameters that are more applicable to microtunnelling than TBM bored tunnel (Table 2). In Figure 6, when the tunnel diameter D is larger than 7m, the unsafe area where the slope ω_{max} in governing always falls inside the area due to allowable settlement. It means that with V_L = 0.5%, in cohesive soil, and the tunnel diameter larger than 7m, the allowable slope ω_{max} = 1/500 need not be assessed.

EFFECT OF C/D ON SUBSURFACE SETTLEMENT

When tunnelling in urban areas, tunnels are sometimes designed below or near existing deep foundations. Therefore, the impact of subsurface settlement on foundations should be investigated. The previous section takes only surface settlements into account. In the case of deep foundations, the settlement and slope assessments are similar as in the case of surface settlement but assessed at the foundation depth L_p. In pile systems, the most important assessment is the ground movement at the tip of the pile due to its effect on the bearing capacity of the pile (NEN-EN 1997-1, 1997).

Figure 7 shows the situation that the tunnel is constructed near a pile. Based on centrifuge tests and empirical data, Mair et al. (1993) show that the subsurface settlement profile distributes as the Gaussian curve. The width of settlement trough at the depth z depends on the depth of the tunnel z_0 via a coefficient K depending on depth as:

$$i = K(z_0 - z) \tag{14}$$

where

$$K = \frac{0.175 + 0.325(1 - z/z_0)}{1 - z/z_0} \tag{15}$$

From Equations 6, 14 and 15, the maximum subsurface settlement can be determined as:

$$\frac{S_{v,max}}{R} = \sqrt{\frac{\pi}{2}} \frac{V_L}{0.175 + 0.325(1 - z/z_0)} \frac{R}{z_0} \tag{16}$$

with R is the tunnel radius.

Applying the "i" value from Equation 14 in Equations 10 and 12, the distance x from the building to tunnel axis corresponding with subsurface settlement u_{max} and subsurface slope ω_{max} are determined.

Figure 8 shows the safe and unsafe areas for the case of a tunnel with diameter D = 6m, and the pile foundation with depth L_p = 6m based on Equation 16. The unsafe area also includes the zone where the pile tip would geometrically fall inside the tunnel. From Equation 11, the $\left(\frac{C}{D}\right)_0$ value such that settlement at the tip of the pile is always less than u_{max} for any distance to the tunnel centre line x can be estimated as:

$$\left(\frac{C}{D}\right)_0 = \frac{0.65 L_P}{D} + \sqrt{\frac{\pi}{8}} \frac{V_L D}{u_{max}} - \frac{1}{2} \tag{17}$$

In Figure 8a, the $\left(\frac{C}{D}\right)_0$ value equals 2.03. It also shows that for x/D from 0.32 to 0.57, there are two values of C/D such that the settlement can reach u_{max}. With x/D more than 0.57, the settlement at the pile tip is always less than u_{max}.

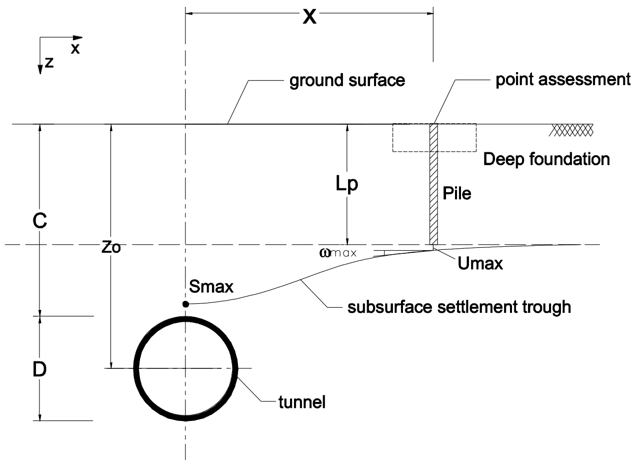
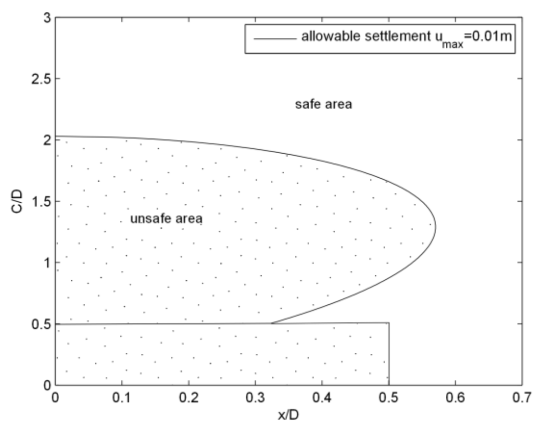
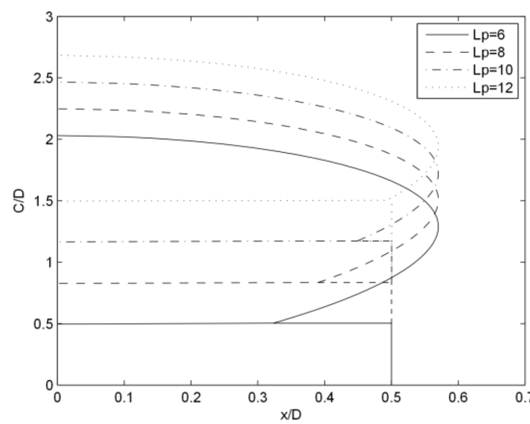


Figure 7. Geometry of a tunnel and existing subsurface structures in a preliminary settlement analysis



(a) L_p = 6m



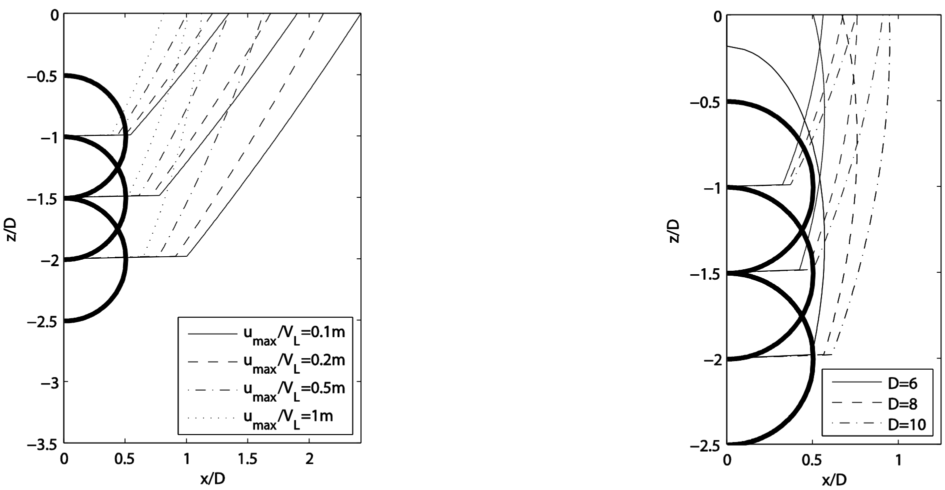
(b) various L_p

Figure 8. Relationship between C/D and x/D for the case of tunnel with D = 6m

Figure 8b presents the safe and unsafe areas for various pile length L_p. It is interesting to note that for various pile length there exists a $\left(\frac{x}{D}\right)_0$ value such that the settlement of the pile tip is always less than u_{max}, which is independent of C/D. In this case $\left(\frac{x}{D}\right)_0$ = 0.57. From Equation 11, the value of $\left(\frac{x}{D}\right)_0$ can be estimated via the distance x_0 from the building to tunnel centre axis as:

$$x_0 = \frac{V_L D^2 \sqrt{\pi}}{u_{max} 4\sqrt{2e}} \approx 0.19 \frac{V_L D^2}{u_{max}} \tag{18}$$

Figure 9a shows the unsafe area of ground movement for the tunnel with D = 6m and various u_{max}/V_L and C/D ratios. With particular C/D values, the smaller u_{max}/V_L ratio is, the larger the unsafe area of ground movements is. Meanwhile, when the tunnel becomes deeper with the increase of C/D value, the unsafe area is wider. Figure 9b shows unsafe areas for different D with V_L = 0.5%. With the same C/D value, the unsafe area increases with increasing tunnel diameter. With a moderate or deep tunnel the surface settlement or settlement near the surface is small. As mentioned above, there is a distance x_0 for a particular tunnel diameter D that the settlement due to tunnelling is always less than u_{max}.



(a) for tunnel with D = 6m (b) for various D with V_L = 0.5%

Figure 9. Ground movement area for tunnel with D = 6m in cohesive soil

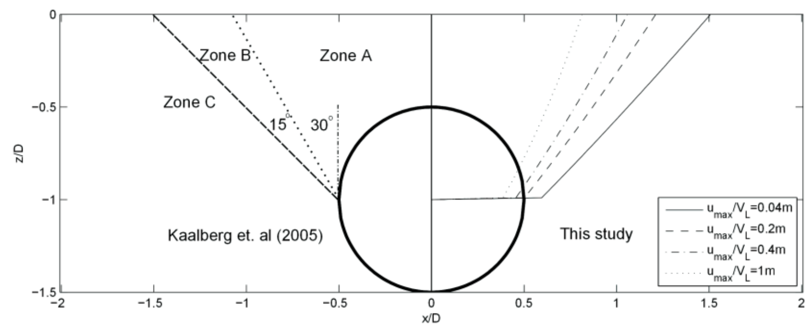


Figure 10. Safe zones in comparing with Kaalberg et al. (2005)

Figure 10 compares the safe areas as indicated by Kaalberg et al. (2005) and this study. Kaalberg et al. (2005) carried out a data analysis of a trial test at the Second Heinenoord tunnel where 63 driven piles, 90 surface settlement points, 29 subsurface points, and 11 inclinometers were measured over a period of two years in order to estimate the impact of tunnelling on piles and pile toes. They also concluded that the safe distance between the piles and tunnels should be more than 0.5D for varying volume loss. Meanwhile, the safe area derived from this study depends on the distance, volume loss and the designed allowable settlement of the building. This figure shows that the larger the allowable settlement is, the closer the piles can be near the tunnel. The unsafe zone A, as indicated by Kaalberg et al. (2005), mostly overlaps the zone where $u_{max}/V_L \geq 0.4$m and the intermediate zone B overlaps the zone where 0.04m $\leq u_{max}/V_L \leq 0.4$m. This indicates that the approach followed in this paper and the results in the Figures 8b and 9a can be used to estimate the safe zone also for different combinations of tunnel diameter, cover and soil conditions.

CONCLUSION

Based on the investigation of surface and subsurface settlement, the extent of safe and unsafe areas due to tunnelling are presented, which will provide a preliminary assessment for the design on the risk of damage for existing structures with allowable settlement u_{max} and slope ω_{max} . For the surface settlement assessment, it is found that there exists a D_0 value such that for D less than D_0 the surface settlement is always less than the allowable settlement u_{max}. It is also found that with large diameter D, the assessment of allowable slope ω_{max} need not be taken into account. For the subsurface settlement, there exists a minimum distance x_0 for particular D that for larger distances from existing structures the settlement is always less than u_{max}. It is also shown that the unsafe area is larger when the C/D ratio increases. Depending on the allowable settlement of the building, designers can determine the impact zone of shield tunnelling on surface buildings or on deep or pile foundations.

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