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Investigation of influence zones induced by shallow tunnelling in soft soils

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ABSTRACT: The extent of the influence zone affected by shallow tunnelling depends on the value of volume loss which normally represents the amount of over-excavation and stress changes induced in the soil. This paper combines upper and lower estimates of volume loss for different soft soils and cover-to-diameter ratios in order to identify the extent of zones around the tunnel influenced by tunnelling. These zones are combined with risk categories of damage of existing buildings in order to determine whether applying mitigating methods or taking additional control measures during tunnelling would be needed for a safe and damage-free tunnel construction. The effects of soil parameters on the influence zones are also investigated to identify their impact and quantity of the requirements for mitigating measures.

1 INTRODUCTION

One of the obstacles in the development of shallow tunnels in urban areas is the high risk of damage on existing nearby buildings. In the assessment of the impact of tunnelling on existing nearby structures, the responses of buildings due to tunnelling have been investigated by many authors Rankin (1988); Netzel (2009); Giardina (2013); Vu et al. (2015). In the study of effects of ground movements on existing buildings, Vu et al. (2015) derived influence zones for a tunnel with different cover-to-diameter C/D ratios. It also shows that the extent of influence zones depends on the ratio of settlement u_{max} and the value of volume loss V_L.

Although the zones induced by tunnelling where nearby structures on piles are impacted, were also estimated in the studies of Kaalberg et al. (2005) and Selemetas et al. (2005) based on analyses of empirical data, theoretical understanding on the extent of influence zones induced by tunnelling is still limited. The influenced zones in these studies were identified in particular projects with the same C/D ratio of approximate 1.9 and a pile-length-to-diameter ratio $L_p/D > 1$. The comparison between the influence zones derived in Kaalberg et al. (2005) and Vu et al. (2015), as can be seen in Figure 1, shows the corresponding ratio of u_{max}/V_L with the boundaries of in fluence zones. With a particular value of surface and subsurface settlement u_{max}, it shows that the volume loss V_L has an important role with the extent of influence zones.

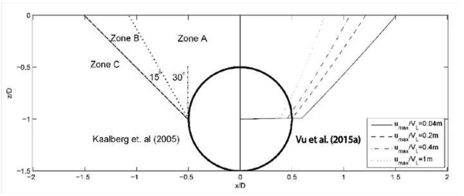
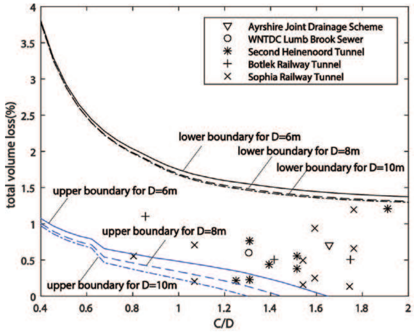
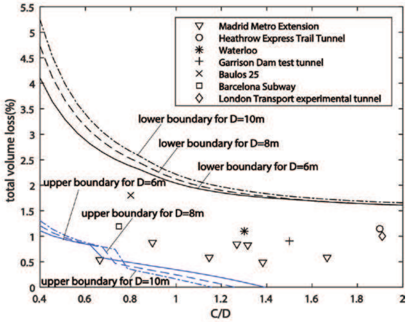


Figure 1. Safe zones in Kaalberg et al. (2005) and Vu et al. (2015).

The value of volume loss therefore is a major parameter in tunnelling design. Various methods for estimating volume loss values in tunnelling have



a) in sand



b) in clay

Figure 2. Boundaries of volume loss in shallow tunnelling.

been published in literature. Based on the empirical data and theoretical analysis, Vu et. al (2016) derived boundaries of volume loss in shallow tunnelling in sand and clay as can be seen in Figure 2. These values of volume loss are estimated by the total of volume loss at the tunnelling face, along the shield and behind the shield. According to Vu et. al (2016), the value of volume loss when tunnelling in peat or soft clay has a wide range. The settlement in these cases of tunnelling thus might be uncontrollable. This means that soil parameters majorly impact on the extent of influenced zones.

The object of this paper is to investigate the variation of influence zones induced by tunnelling in the relation to damage categories in a damage risk assessment for the buildings and soil parameters in order to find out the solutions for reducing the extent of influence zones.

2 ON THE VARIATION OF INFLUENCE ZONES WITH DIFFERENT CATEGORIES OF DAMAGE RISK ASSESSMENT

In order to estimate the impact of volume loss and the variation of the extent of the zones affected by tunnelling in relation to the different damage categories, allowable settlement values $u_{max} = 10$, 50 and 75 mm corresponding to the transitions between categories I, II, and III of damage risk assessment in Table 1 proposed by Rankin (1988) are applied. The analysis is carried out for a case with tunnel diameter D = 6 m in the examples shown in this paper.

Figure 3 shows the impact of the relative influence distance from the tunnel axis to surface buildings x/D and the C/D ratio in these damage categories. In this figure, depending on the relative influence distance x/D, it is indicated whether additional ground improvement and/or careful monitoring control is required, or it should be possible to tunnel safely without additional measures. These relative influence distances are estimated for the three above risk categories.

Not surprisingly, this shows that if the tunnel axis is well separated from the closest foundation (x > D), the impact of a settlement trough on the building is limited. Similarly, if the tunnel is relatively deep, the settlements are spread over a wider area and even if the tunnel passes below the building, the impact on the building is limited if tunnelling is well controlled. Only for tunnels that are close to the building foundation and at limited depth, the impact is such that additional mitigating measures will be necessary and careful control of the tunnelling process alone is not sufficient to avoid damage.

Figure 4 shows the effects of tunnel diameter on the relative influence distance where tunnelling in clay for risk category I. In the case of C/D = 0.4 (the lowest C/D ratio value in this study), if buildings are at a relative influence distance x/D less than 0.8, ground improvement or other measures should be considered. When the C/D ratio ranges from 0.8 to 2, careful monitoring

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
I	Less than 1/500	Less than 10	Negligible; superficial damage unlikely
II	1/500–1/200	10–50	Slight; possible superficial damage which is unlikely to have structural significance
III	1/200–1/50	50–75	Moderate; expected superficial damage and possible structural damage to buildings, possible damage to relatively rigid pipelines
IV	Greater than 1/50	Greater than 75	High; expected structural damage to buildings. Expected damage to rigid pipelines, possible damage to other pipelines

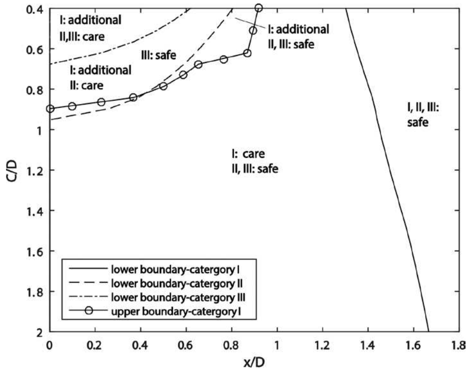


Figure 3. Relative influence distances due to tunnelling with D = 6 m in clay with Risk Categories I, II, III: additional: require additional ground improvement; care: require careful control; safe: safe area with allowable settlement.

is required during the tunnelling progress, but additional measures need not be necessary. In the case of C/D ratios larger than 1, surface buildings will normally deform less than $u_{max} = 10$ mm. As long as the TBM is properly operated, it can also be seen from this figure that even if the buildings are directly above the tunnel, ground improvement methods may not be necessary for tunnelling with an allowable settlement $u_{max} = 10$ mm with the C/D ratio larger than 1. However, when the relative influence distance x/D is less than 2, careful control is necessary.

In order to apply these results to shallow tunnelling, they should be compared to data observed from existing tunnelling cases. The validation of the impact of shallow tunnelling on ground movement in soft soils is shown in Figure 4 for relative influence distances from the tunnel axis to the existing surface buildings. The observed settlement data in shallow tunnelling cases described in

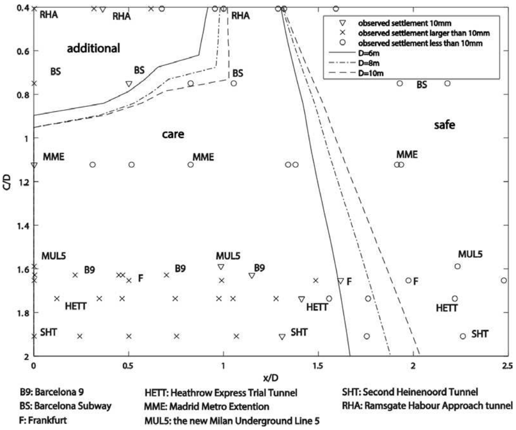


Figure 4. Comparison of relative influence distances to shallow tunnelling cases.

Table 2. Relative distance x/D in shallow tunnelling cases.

Tunnel	D (m)	C/D	u (mm)	x/D	Construction method	Ground improvement
Barcelona Line 9	9.4	1.63	10.8	9.4	EPB machine	jet grouting compensation, structural jacking
			11.1	1.1		
			14.9	0.7		
			17.9	0.8		
			20.6	0.4		
			22.4	0.0		
Barcelona Subway	8	0.75	0,2	2,2	–	Jet grouting
			0,3	1,9		
			1,3	0,8		
			1,5	1,1		
			10	0.5		
			23.4	0		
Frankfurt	6.5	1.65	3.0	3.0	Shield with bolted concrete segments	–
			4.9	2.5		
			7.8	2.0		
			10	1.6		
			12.8	1.5		
			20.9	1		
			28.6	0.5		
			32.1	0		
Heathrow Express Trail Tunnel, UK	8.5	1.735	0.9	3.3	Open face	–
			2.8	2.2		
			5.8	1.8		
			8.2	1.6		
			10	1.4		
			12.5	1.3		
			16.5	1.0		
			18.7	0.9		
			26.6	0.8		
			34.3	0.5		
			36.6	0.3		
			38.8	0.1		

(*Continued*)

Table 2. (*Continued*).

Tunnel	D (m)	C/D	u (mm)	x/D	Construction method	Ground improvement
Madrid Metro Extension	8.88	1.12	0.6	1.9	EPB machine	–
			1.4	1.9		
			2.2	1.4		
			4.6	1.4		
			4.9	0.8		
			7.4	0.5		
			8.7	0.3		
			10	0		
Milan Underground Line 5	6.7	1.59	0.3	3.1	EPB machine	Grout injection
			1.6	2.2		
			10	1		
			21	0		
Ramsgate Habour Approach Tunnel	11	0.41	0.7	1.3	Perforex pre-vaulting method	Fiberglass
			1.7	1.6		
			1.9	1		
			2.7	1.3		
			4.8	0.7		
			8.9	1		
			10	0.4		
			11.9	0		
			12.5	0.6		
			13.1	0.3		
Second Heinenoord Tunnel	8.3	1.91	1.4	3.5	Slurry machine	–
			3	2.3		
			5.3	1.8		
			10	1.3		
			15.1	1.1		
			21.8	0.8		
			26.4	0.5		
			29.3	0.2		
			30.1	0		

Table 2 are taken from surface settlement trough data. Since there is only a small number of existing tunnels which have C/D values lower than 2 and have detailed surface settlement monitoring data available, the discussion here will provide recommendations for future shallow tunnelling.

- In Figure 4, the cases with observed settlements of more than 10 mm are derived from measuring points at or nearby the vertical axis of the tunnel where the surface settlements reach the maximum values as indicated in Vu et al. (2015). Settlements further away from the tunnel axis in these projects, but still in the zone requiring attention are equal or less than 10 mm.
- Settlements of approximately 10 mm are almost always recorded in the zone indicating special care and for projects where ground improvement methods were used and in the normally safe areas in the case of the Frankfurt and Heathrow tunnels, which were constructed without ground improvement.
- For settlements less than 10 mm, there are two observed cases, namely the Barcelona Subway and the Madrid Metro Extension, where ground improvement methods were applied and followed with careful monitoring. For the other projects no measures were taken and the settlements concur with our prediction.

In the areas that additional measures are needed, Ramsgate Habour Approach tunnel was constructed by Perforex pre-vaulting method combined with the fiberglass ground improvement methods Bloodworth (2002). This tunnel has a C/D ratio of 0.41, but is not strictly a bored tunnel.

3 EFFECTS OF SOIL PARAMETERS ON INFLUENCE ZONES

In order to identify the method and quantity of ground improvement that should be applied when tunnelling, the impacts of soil parameters on relative influence distances x/D are investigated. In this study, the effects of the cohesion c, the angle of internal friction φ and the modulus of elasticity E on the boundaries of influence zones are studied.

Figure 5 shows the dependence of the relative influence distance x/D on the cohesion c in the case of tunnelling with D = 6 m in soil with angle of internal friction φ = 35° and elasticity modulus E = 12000 kN/m². When the cohesion c increases, the unsafe relative distance x/D decreases. Moreover, it can also be seen that the gaps between lower boundaries are larger than the gaps between upper boundaries. Based on this analysis, in the case of tunnelling with a small C/D ratio, increasing the value of the cohesion c can be an effective method in order to reduce the safe relative influence distance x/D. When the value of the cohesion c is approximate 21 kN/m², the lower boundary becomes 0 with C/D = 0.4. It means that if ground treatment methods can improve the cohesion to 21 kN/m², the risk of settlements more than 10 mm can be limited, but careful control on grouting and support pressure still needed.

The effect of the angle of internal friction φ on the relative influence distance x/D is shown in Figure 6. In this analysis, the angle of internal friction φ is assessed in the range from 20° to 58° according to Fujita (1998) which corresponds to the maximum angle of internal friction of a grouted soil for a tunnel in soil with cohesion c = 7 kN/m² and elasticity modulus E = 12000 kN/m². It can be seen that when the angle of internal friction φ increases, the relative influence distance x/D becomes smaller. However, due to the limitation of increasing of the angle of internal friction φ further, a relative influence distance x/D will remain. Based on these results, increasing the angle of internal friction φ can be a useful method to reduce the relative influence distance x/D.

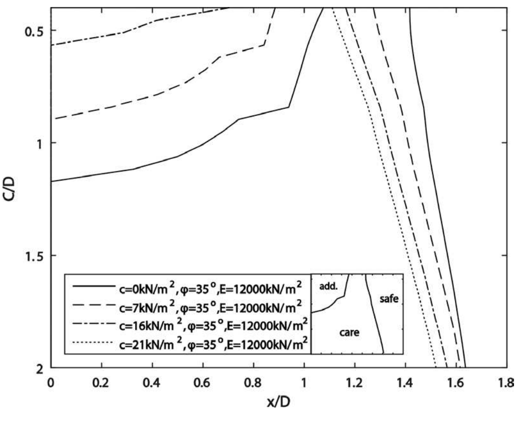


Figure 5. Effect of cohesion c on relative influence distance x/D in the case of tunnelling with D = 6 m.

Figure 7 shows an opposite impact of increasing the modulus of elasticity E on the relative influence distance x/D due to tunnelling for a tunnel in soil with cohesion c = 7 kN/m² and angle of internal friction φ = 33°. This figure shows that the higher the value of the elasticity modulus E is, the larger the relative influence distance x/D is. This is due to the increasing influence of heave at the tail, which leads to more compensation of the settlement of tunnelling and a reduction of the total volume loss. However, in practice, when increasing the cohesion c value and angle of internal friction φ value, the modulus of elasticity E of the soil also increases. In this case, it follows that the volume loss at the tunnelling face can be reduced but it is difficult to fully compensate any settlement at the tail gap.

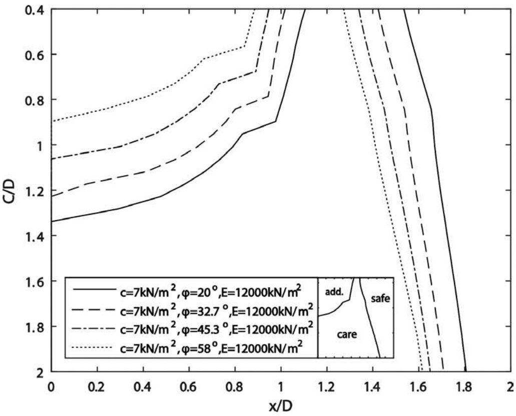


Figure 6. Effect of angle of internal friction φ on relative influence distance x/D in the case of tunnelling with D = 6 m.

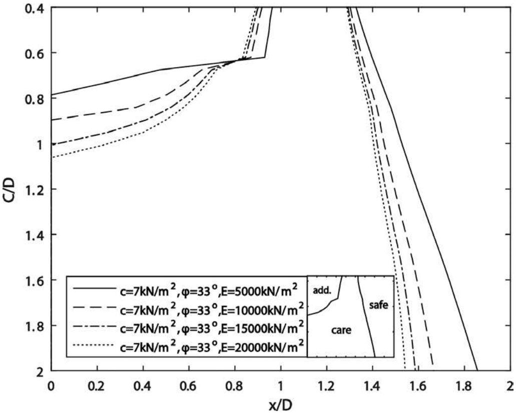


Figure 7. Effect of modulus of elasticity E on relative influence distance x/D in the case of tunnelling with D = 6 m.

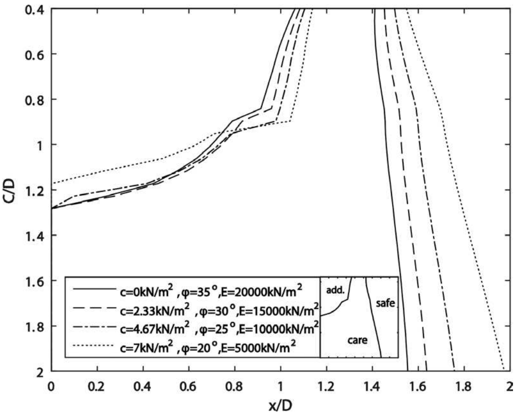


Figure 8. Combination influence of soil parameters on relative influence distance x/D in the case of tunnelling with D = 6 m.

Figure 8 shows the relationship between the C/D ratio and the relative influence distance x/D in the case of shallow tunnelling with diameter D = 6 m with the combination of changing all above soil parameters. With a given distance from the existing buildings to the tunnel axis, required soil parameters can be estimated in order to achieve settlements less than a given allowable settlement. It can be seen that although increasing stiffness and strength has opposite impacts on the width of the influence zone, the combination of these effects can lead to a reduction of the influence zone. On the basis of this analysis, designers can start to choose suitable ground improvement methods and identify quantities of ground treatment, for example, jet grouting, soil mixing and other mitigating measures.

4 CONCLUSION

By combining the upper and lower estimates of volume loss and ground movement analysis, the boundaries of influence zones induced by shallow tunnelling are derived both for surface and subsurface in this paper. The combination of influence zones with different categories of risk damage assessment is investigated in order to identify the zones where mitigating measures should be applied or careful monitoring is needed. Although there is only a small number of existing case studies, it shows a good agreement between the analysis results and observed data. In order to allow tunnelling in areas, where soil conditions are expected to lead to too large surface settlements without additional measures (unsafe zones), this study also shows that by improving soil properties, the boundaries of influence zones can be controlled. This analysis provides a theoretical basis to identify the mitigating methods and the required quantity of soil improvement with the aim of safe and damage-free tunnel construction.

REFERENCES

Bloodworth, A.G., 2002. *Three-dimensional analysis of tunnelling effects on structures to develop design methods*. Ph.D. thesis, University of Oxford.

Fujita, Y., Ishimaru, R., Hanai, S., Suenaga, Y., 1998. Study on internal friction angle and tensile strength of plain concrete. *Proceedings of fracture mechanics of concrete structures FRAMCOS 3*, 325–334.

Giardina, G., 2013. *Modelling of settlement induced building damage*. Ph.D. thesis, Delft University of Technology, Delft, The Netherlands.

Kaalberg, F., Teunissen, E., Van Tol, A., Bosch, J., 2005. Dutch research on the impact of shield tunnelling on pile foundations. In*: Proceeding of the International Conference on Soil Mechanics and Geotecnical Engineering*. Vol. 16. AA Balkema Pubishers, p. 1615.

Netzel, H.D., 2009. *Building response due to ground movements*. Ph.D. thesis, Delft University of Technology. Delft, The Netherlands.

Rankin, W., 1988. Ground movements resulting from urban tunnelling: predictions and effects. *Geological Society, London, Engineering Geology* Special Publications 5 (1), 79–92.

Selemetas, D., Standing, J., Mair, R., 2005. The response of full-scale piles to tunnelling. In: Proceedings of the 5th *International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*. Taylor and Francis, pp. 763–769.

Vu, M.N., Broere, W., Bosch, J.W., 2015. Effects of cover depth on ground movements induced by shallow tunnelling. *Tunnelling and Underground Space Technology* 50, 499–506.

Vu, M.N., Broere, W., Bosch, J.W., 2016. Volume loss in shallow tunnelling. *Tunnelling and Underground Space Technology* 59, 77–90.