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Comparison of rectangular and circular bored twin tunnels in weak ground

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Abstract

The recent innovation of a rectangular tunnel boring machine (TBM), and its use in the Hongzhuan Road tunnel underpass by the China Railway Engineering Group (CREG), has revitalized shallow depth soft soil tunneling. This paper presents the findings of a numerical study using PLAXIS to determine the surface settlements and moments produced in tunnel linings for circular and rectangular twin tunnels. The effects of the relative positions of twin tunnels, critical distances, volume losses, depths of burial, and tunnel sizes for both circular and rectangular tunnels are the key parameters of this investigation. The results indicate that rectangular tunnels are suitable for shallow depths in weak ground as they have lesser settlement compared with circular tunnels. This is crucial for tunneling beneath important structures such as railway lines and existing roads. However, the maximum bending moment produced in the rectangular tunnel lining is higher than that for circular tunnels. The use of rectangular TBMs is an unconventional method in modern day tunneling; however, the analysis in this project recommends that tunnel industry engineers consider this method for shallow depth weak ground tunneling.
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Keywords: Twin tunnels; Clay; Numerical modeling; Rectangular TBM

1 Introduction

Worldwide, rapid population growth in major cities has resulted in increased pressure on existing transportation systems. With underground transportation systems already in place, newly constructed tunnels may need to be constructed in close proximity to each other to make efficient use of the underground space. Studies have been undertaken to consider the effects of twin tunnel construction on tunnel lining stress and ground surface settlement.

Peck (1969) developed a semi-empirical model to predict the surface settlement of closely-spaced tunnels in soft clay. Physical modeling of this theory was tested by Kim, Burd, and Milligan (1998), showing that there is an effect on the ground surface settlement. In Japan, Yamaguchi, Yamazaki, and Kiritani (1998) reported change in the lining stress of an existing tunnel, owing to the construction of a new adjacent tunnel. For closely-spaced tunnel construction, ground surface settlement and lining stress have increased influence from superimposition effects, as compared with single tunnel construction.

Hefny, Chua, and Zhao (2004) identified numerous factors affecting the critical distance between twin tunnels, primarily using circular bored tunnels. Critical distance refers to the capacity of adjacent tunnels to accommodate change in structural loadings, combined with the criteria for settlement above the tunnels. The volume loss, the relative position of newly-bored tunnels, the depth of cover, the lining thickness, and the critical distance were identified as key factors affecting the maximum bending moment produced

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within the tunnel lining. Note that the depth of burial refers to the depth to the center of the tunnel from the ground surface, whereas cover depth refers to height of material between the top center of the tunnel and the ground surface. The key findings of their study included:

(1) Increase in induced bending moment in tunnel lining as volume loss increased;
(2) Increased depth leads to increased moment;
(3) Reduction in bending moment when the relative position of a newly-bored tunnel is beneath the existing tunnel (piggyback);
(4) Increase in bending moment for a stiffer lining.

Ngoc, Dias, Pierpaolo, and Inni (2014) investigated the critical distance between twin circular bored tunnels. Their investigation suggested a minimum clear distance between twin tunnels of $2d$, where d is the diameter of the tunnel. Any decrease in critical distance below $2d$ would lead to experiencing increased stresses in the tunnel lining. Elshamy, Attia, Hafez, and Fawzy (2013) investigated the effect of tunnel shape on twin tunnel interactions (induced bending moments and ground surface settlement), and reported a suggested application for each tunnel type. Circular tunnels were suggested to be the most suitable tunnel shape for general projects.

This study further pursues the investigation conducted by Elshamy et al. (2013), by including the effect of the parameters suggested by Hefny et al. (2004) on rectangular tunnel shapes. Recent technology advancements as presented by the China Railway Engineering Group (CREG) have led to the development of rectangular tunnel boring machines (TBMs), as shown in Fig. 1. TBMs have also been considered in this study.

2 Numerical analysis setup

2.1 Geometry, mesh, and boundary conditions

Numerical analysis was conducted using a two-dimensional (2D) finite element analysis program, PLAXIS 2D, to predict the surface settlement and bending moment produced in the twin tunnel lining. In that regard, PLAXIS 3D is more 'realistic' in determining settlement and bending moments, as it is more accurate relative to real-life case studies. However, for validation with previous studies, PLAXIS 2D was considered as appropriate for this study.

Two tunnel types were investigated in this study: circular tunnels for a point of comparison with existing literature, and rectangular tunnels for comparison with the circular tunnels. All model cases were twin tunnel cases, as representative of urban tunnel construction. Tunnel sizes were varied between 6 m, 9 m, and 12 m. The cross-sectional area for comparing rectangular and circular tunnels is different; however, the intended road lane capacity is the same. The Australian Roads and Maritime Services (2016) agency provided a minimum of 4.6 m vertical clearance for trucks. Drainage structures for the horizontal clearance of the rectangular tunnel shape are incorporated into these dimensions. Additional allowances for tunnel space proofing have not been included in this study.

Each model required numerical analysis in three stages: (a) the initial conditions prior to tunnel construction, (b) single tunnel construction, and (c) adjacent tunnel construction. The initial condition simulated the ground settlement of the soil under the self-weight of the soil. Single tunnel construction simulates staggered twin tunnel staging to reduce the interaction of stresses. Adjacent tunnel construction allows for determining the combined effects on surface settlement and bending moments produced in the tunnel lining. The same approach was used for both tunnel shapes, and no consideration was made for staged excavation prior to tunnel lining installation. Although this may capture the key differences based on tunnel shape, it may not consider the inherent differences between the rectangular and circular TBMs. The selection of a mesh was determined based on a comparison between the five available sizes on PLAXIS 2D, including very coarse, coarse, medium, fine, and very fine. A comparison between each of the mesh sizes determined that the difference between each size is negligible, as shown in Fig. 2.

A plain strain model was used, as the length of the tunnel excavation is significantly longer than the width of the excavation, making strain in the z direction zero. As shown

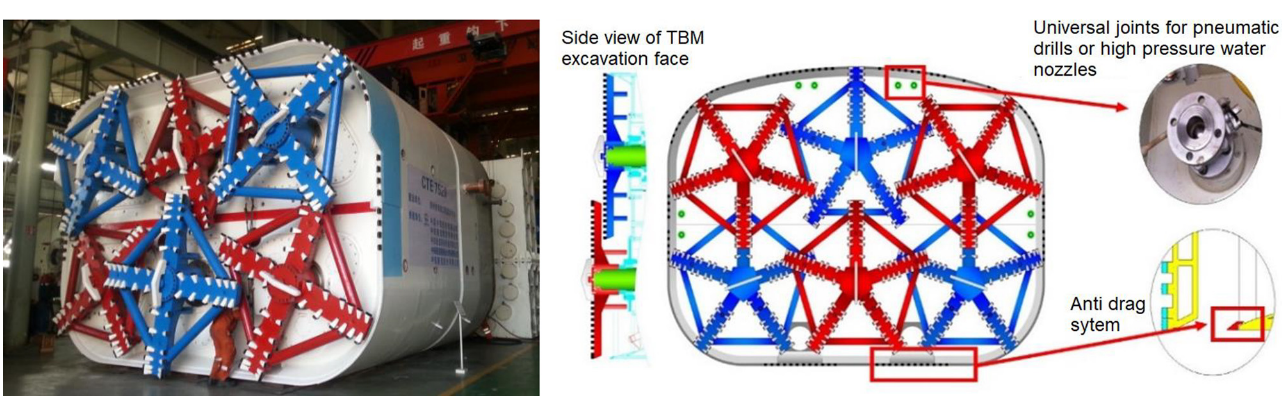


Fig. 1. Rectangular tunnel boring machine (TBM) and its key features [after China Railway Engineering Group (CREG), 2016].

in Fig. 3, boundary conditions of the models were fully fixed at the base, free at the surface, and normally fixed on the sides. The size of the analysis was kept consistent, with the width of the boundary being 25*d* wide and 8*d* in height for the largest tunnel.

The modeling conducted for this report was based on the use of a 6-node system. There is a higher degree of accuracy when modeling is undertaken using a higher number of nodes. In the case of 3D modeling specifically for tunnels, there is a greater accuracy in the measurement of settlement and the calculation of moments, as 3D settlement is considered. Modeling based on a 6-node system and a 15-node system did not show a major difference in the settlement or the moment coefficient. Thus, the 6-node system was utilized, for a faster analysis time.

2.2 Soil and tunnel lining properties

The soil and tunnel lining properties presented in Table 1 were based on previous literature, to allow for validation of the numerical analysis. The soil was chosen to be weak ground comprised of clay, as this is the material of interest for operation of the rectangular TBM. The properties for clay were adapted and slightly adjusted from Hefny et al. (2004). For simplicity, water and consolidation were not considered in this investigation; however, if considered, soft clay properties should be adopted (Zhang, Wu, Shen, Hino, & Yin, 2016, Chen, Shen, Yin, Xu, & Horpibulsuk, 2016, Shen, Wu, Cui, & Yin, 2014). Anisotropy (Yin, Chang, Hicher, & Karstunen, 2009; Yin, Chang, & Karstunen, 2010), inter-particle structure effects (Yin, Karstunen et al., 2011), and the time-dependency behavior of clay (Yin, Mahdia et al., 2011; Yin, Zhu, Yin, & Ni, 2014) were also not considered in this investigation, but should be adopted for soft clay analysis. Tunnel lining properties were based on the previous studies for circular tunnels conducted by Sebastian and Nadarajah (2000). For simplicity of analysis, the material model was Mohr-Coulomb for the soil, and elastic for the tunnel lining.

2.3 Modeling conditions

Five conditions, including tunnel shape, relative rotation, size, depth, and separation distance were modeled as part of the PLAXIS analysis. The key point of comparison is between the shape of the tunnels, and the effect of each of the conditions on the surface settlement and bending moment produced in the tunnel lining. These parameters, including the relative rotation between a twin tunnel alignment, tunnel size, tunnel depth of burial, and critical distance, were identified as integral aspects of tunnel construction.

2.3.1 Relative rotation

During construction of twin tunnels, the arrangement of the tunnels can play a major role in reducing the impacts of surface settlement and moments induced in linings of twin tunnels. Studies by Hefny et al. (2004) have been undertaken for circular tunnels, but a similar study for correlation with rectangular tunnels has not been considered. The position of Tunnel 1 was maintained, whilst Tunnel 2 was rotated in 15 degree increments commencing from the horizontal, as depicted in Fig. 4.

2.3.2 Tunnel size

The tunnel diameter size for the circular tunnels was varied between 6, 9, and 12 m. For rectangular tunnels, the cross-sectional tunnel area was based on a vertical height clearance of 4.6 m, and a horizontal width identical to that of circular tunnels. The depth to the center of the tunnels was maintained at 20 m below the surface, with a center-to-center distance of 2.5*d*.

2.3.3 Tunnel depth

The twin tunnel depth of burial was varied between 0.8*d*, 1.3*d*, 1.7*d*, 2.5*d*, 3.3*d*, 4.2*d*, and 5.0*d*. The center-to-center distance between twin tunnels was maintained at 2.5*d*. The tunnel size for circular tunnels was 6 m in diameter, and a normalized equivalent radius (r) of a rectangle was used based on the length (L) and breadth (B) dimensions,

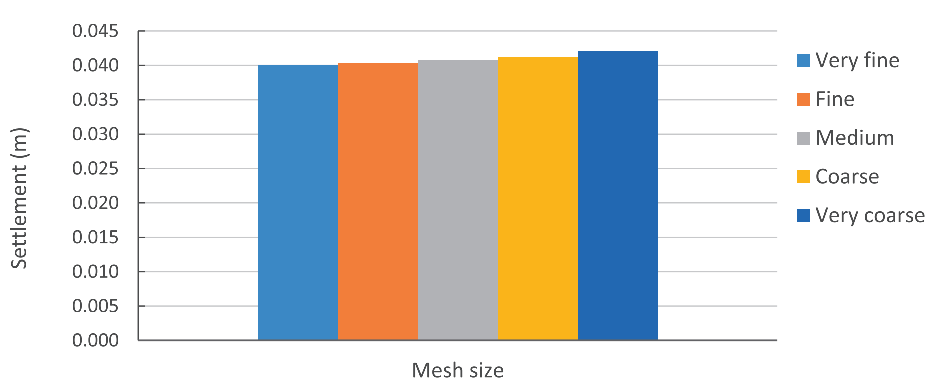


Fig. 2. Settlement versus mesh size.

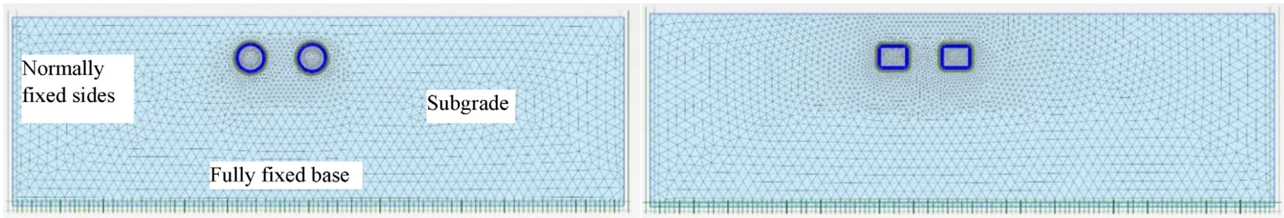


Fig. 3. Mesh and boundary conditions, (a) for twin circular tunnels and (b) for twin rectangular tunnels.

Table 1
Material properties for numerical model.

Property	Unit	Soil	Tunnel lining
E	kN/m^2	10 000	—
E	MN/m^2	—	32 000
γ_{unsat}	kN/m^3	15	—
γ_{sat}	kN/m^3	18	—
k_o		0.577 4	—
c'	kN/m^2	5	—
v'		0.35	0.15
ϕ	°	25	—
GWL	m	—	—
e_o		1	—
OCR		1	—
$EA_1 = EA_2$	kN/m	—	9.6×10^6
EI	kN m^2/m	—	72×10^3
t	m	—	0.3
w	kN/m/m	—	7.0
V_{loss}	%	—	1.5

Note: E is Elastic stiffness, γ_{unsat} is unsaturated unit weight, γ_{sat} is saturated unit weight, k_o is lateral coefficient of earth pressure, c' is effective cohesion, v' is Poissons ratio, ϕ is effective friction angle, GWL is ground water level, e_o is initial void ratio, OCR is over consolidation ratio, EA is axial stiffness, EI is flexural rigidity, t is thickness of tunnel lining, w is weight of tunnel lining per m run, and V_{loss} is volume loss.

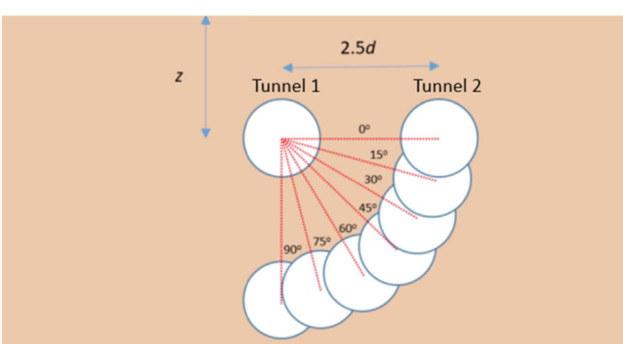


Fig. 4. Relative positions of twin tunnels.

as shown in Eq. (1). This was completed to allow for comparison of the cover-to-depth ratio between circular and rectangular twin tunnels.

$$r = \sqrt{\frac{B \times L}{\pi}}. \qquad (1)$$

For a wider application to tunnel sizes, dimensionless results were presented for the bending moment, by finding the moment coefficient. Equation (2) was used to determine the moment coefficient (k):

$$k = \frac{M_{max}}{(\gamma_s \times H \times r^2)}, \qquad (2)$$

where M_{max} is maximum moment in tunnel lining, γ_s is unit weight of soil, H is height of cover above tunnel, and r is radius of tunnel.

2.3.4 Critical distance

The critical distance refers to the distance between twin tunnels prior to a significant increase in impacts on the tunnels caused by close proximity. This analysis has been undertaken for circular tunnels by Ngoc et al. (2014). However, with the new rectangular TBM technology, further investigation has been undertaken. The center-to-center distance between the twin tunnels was varied by 1.5d, 2d, 2.5d, 3d, 4d, 5d, 6d, 7d, and 8d, where d is the tunnel diameter, as mentioned above and shown in Fig. 5. In the case of rectangular twin tunnels, an equivalent diameter was utilized for the calculation of the center-to-center distance. The depth to the center of the tunnel was maintained at 20 m beneath the surface, and the tunnel diameter was maintained at 6 m.

3 Results

The results from each of the conditions outlined in Section 2.3 are summarized and presented in this section.

3.1 Effect of depth of burial

The depth of burial is a factor which must be considered for tunnel construction. This factor is project-dependent, and thus results have been presented in a dimensionless manner, with a cover-to-diameter ratio. This ratio was increased from 0.5 to 5.6 between each of the tunnels. These numbers were based on the depths outlined in Section 2.3.3. In the following plots, when the cover material

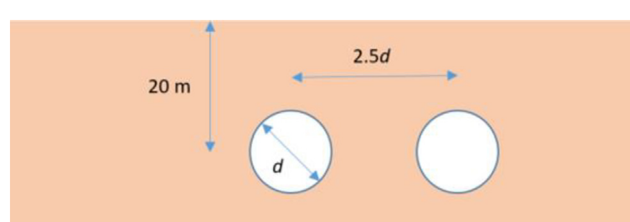


Fig. 5. Center-to-center distance between twin tunnels.

above the tunnel is 3 m and the diameter of the tunnel is 6 m, the cover to diameter ratio will be 0.5. Increasing the depth of burial means that the cover-to-diameter ratio will be higher.

Figure 6(a) depicts the effect of the cover-to-diameter ratio against the maximum surface settlement produced by the twin tunnels. For shallow depths up to a cover-to-diameter ratio of approximately 1*d*, the rectangular twin tunnels have a decreased amount of settlement as compared to the circular tunnels. Beyond the 1*d* ratio, the circular tunnel settlement is significantly less than the rectangular tunnel shape.

The moment produced in the rectangular twin tunnels is up to three times higher than that in the circular tunnels, as shown in Fig. 6(b). In terms of the design and construction of lining material, this would require a greater amount of steel reinforcement, to compensate for the increase in the bending moment.

At a depth of burial of 0.5*d* below ground level, the maximum settlement obtained was:

(1) 59 mm for circular tunnels,
(2) 55 mm for rectangular tunnels.

Although the maximum settlement difference between each of the tunnel shapes is only 4 mm, there is a significant difference in the range of settlement directly above the tunnels. The settlement values directly above the circular twin tunnels are between 44 mm and 59 mm, within a range of 15 mm. The settlement range for rectangular twin tunnels is between 46 mm and 55 mm, within a range of 9 mm. This range of settlement is nearly half that of the circular tunnels.

The extent of surface settlement varied for each of the tunnel shapes. The circular tunnel had a large portion of the total settlement located directly above the tunnel, whereas the rectangular tunnels spread the settlement over a larger area. The extent of settlement for each tunnel shape where settlement was at least 4 mm is:

(1) 27–118 m for circular tunnels,
(2) 30–107 m for rectangular tunnels.

The extent of the settlement is also less for rectangular tunnels than for circular tunnels, with an approximately 14 m reduction in the total surface extent. For the construction of tunnels under important structures, such as arterial roads or highways, there is a need for limited settlement. In circumstances of very shallow cover, the use of a rectangular tunnel shape may reduce the total settlement value, as well as the extent of the settlement. However, circular tunnels limit the bulk of the settlement to directly above the tunnel, which can be an advantage for remediating damaged areas, although the degree of damage might be higher. The circular tunnels' reduced bending moments are also a significant advantage over rectangular tunnels.

3.2 Tunnel size

The size of the twin tunnels has a major impact on both the bending moment in the tunnel lining and the settlement. For this case, three different tunnel sizes were selected for both circular and rectangular tunnels. Tunnel centers were kept at the same level and tunnel dimensions were increased symmetrically about this point, and thus, the larger tunnels have less cover. When interpreting the graphs below, the smaller cover-to-diameter ratio refers to the larger-sized tunnels.

For rectangular tunnels, the surface settlement is higher than that of the circular tunnels for this particular 20 m depth, as shown in Fig. 7(a). As would be expected for both tunnel types, the larger-sized tunnels have a significantly greater amount of maximum settlement than the smaller-sized tunnels.

Figure 7(b) depicts the tunnel size against the moment coefficient. For rectangular tunnels, a greater variety of sizes is required to ascertain any relationships between size and the maximum moment produced, particularly in relation to the apparent low point. For circular tunnels, as the tunnel size decreases, the moment produced in the tunnel lining decreases. Once again, the moment produced within rectangular tunnels is significantly higher than that in circular tunnels.

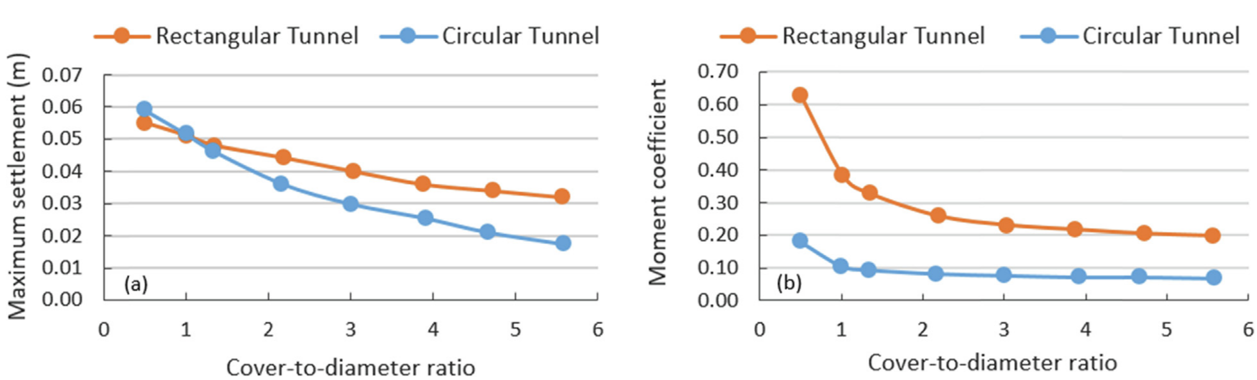


Fig. 6. Effect of cover to diameter ratio on (a) the maximum surface settlement and (b) the moment coefficient.

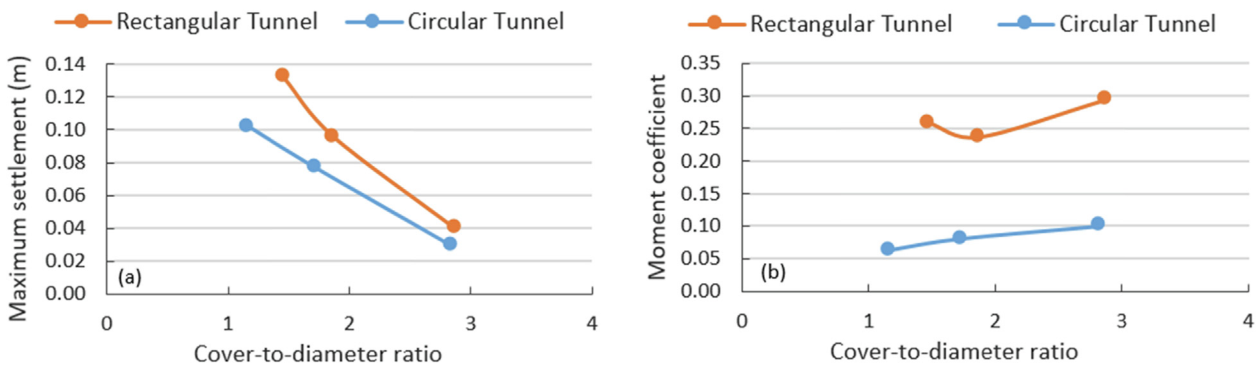


Fig. 7. Effect of tunnel size on (a) maximum surface settlement and (b) moment coefficient.

3.3 Critical distance

In similarity to the previous studies above, the rectangular tunnels have a higher moment coefficient that is approximately three times greater than that of the circular tunnels, as depicted in Fig. 8(a). Both tunnels display a significant increase in bending moment when the center-to-center distance is less than 2.5*d*–3*d*, with circular tunnels being the lesser of the two values.

Volume loss refers to the reduction of the cross-sectional area of the tunnel face during mechanized tunneling excavation, owing to external soil pressure. Volume loss varies depending on soil type, with typical values according to O'Reilly and New (1982) including 1%–2% (clay), 0.2%–1% (dense sand), and 0.5%–1% (sandy clay). A variation of the volume loss from the adopted value of 1.5% for this numerical analysis would result in significantly different results. For lower volume losses, the moment coefficient would be lower than the values displayed in Fig. 8(b), which utilizes the 1.5% volume loss as per Table 1. Thus, this effect of volume loss on the moment coefficient should be considered when analyzing the results. When tunnels are closely spaced, overlapping of the surface settlement curves occurs, resulting in increased settlement. Figure 9 shows that settlement of twin circular tunnels is greater for center-to-center distances less than approximately 2.5*d*. This value of 2.5*d* supports the investigation conducted by Hefny et al. (2004). For rectangular tunnels, a significant increase in settlement is displayed beyond 5*d* as shown in Fig. 9. Comparing both critical distances, the circular tunnels can be spaced at a closer distance with a reduced effect on settlement compared to rectangular tunnels.

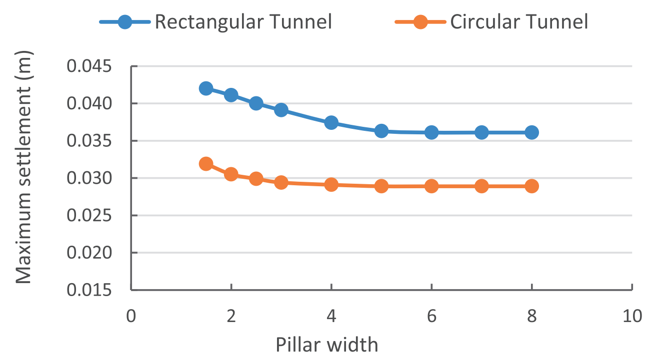


Fig. 9. Effect of critical distance on the maximum surface settlement.

The depth of burial for twin tunnels remained constant for this modeling at 20 m beneath the surface. This relatively deep burial depth explains the significant difference in settlement between the rectangular and circular tunnels. From Section 3.1, the main finding was the better

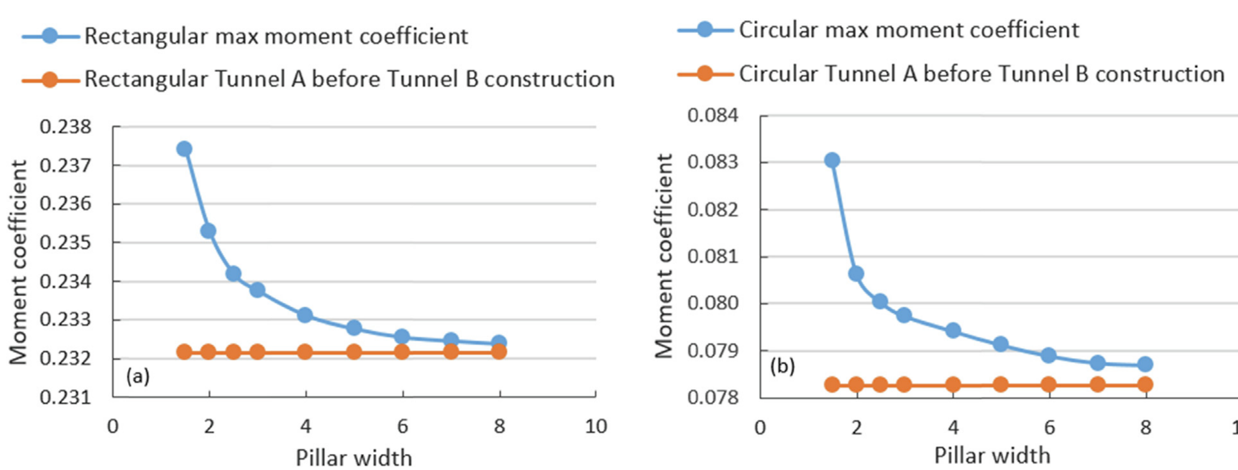


Fig. 8. Effect of moment coefficient versus critical distance on (a) rectangular twin tunnels and (b) circular twin tunnels.

performance of rectangular tunnels for shallow depths as opposed to circular tunnels. This difference in performance is largely attributed to the way in which stress is distributed over the tunnel shape. The circular shape, and in particular the resultant arch effect, has been proven to distribute the vertical stresses more efficiently than the beam effects of the roof of the rectangular tunnels, especially for deep tunnels.

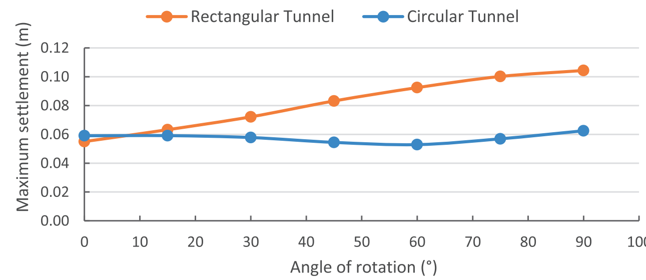


Fig. 11. Effect of relative position on maximum surface settlement.

3.4 Relative rotation of twin tunnels

The positions of twin tunnels relative to each other has been previously investigated, and has been shown to have a significant impact on both tunnels, for the moment produced and for the combined settlement. Figure 10 shows the effect of changing the position of the twin tunnels on the maximum moment produced in the tunnel lining. For parallel twin tunnels (0°), the maximum moment produced in both tunnels is significantly less than that in piggyback tunnels (90°). Between 0° and 45°, there is an increase in the maximum bending moment, but at a decreasing rate (for the tunnel B). The bending moment for the tunnel constructed first (tunnel A) remains largely the same for all angles, with a slight bending moment relief for piggyback tunnels. Similar to findings of Hefney et al. (2004), the piggyback tunnels, with a second tunnel deeper than the first, will have larger bending moments, because the horizontal earth pressure increases with depth. In the case of adjacent tunnels, the horizontal earth pressure remains the same, and therefore the bending moments are lower than in piggyback cases.

Figure 11 depicts the effect of the position of the tunnels against the maximum settlement. For rectangular tunnels, parallel tunnels (0°) have the least settlement, and piggyback tunnels have the most. For circular tunnels, there is only a slight variation in the maximum settlement between all angles.

3.5 Empirical and analytical method comparison

A comparison between the results obtained for circular tunnel was made with existing empirical and analytical methods. The empirical methods of O'Reilly and New (1982) and Mair, Taylor, and Bracegirdle (1993), along with the analytical method by Loganathan and Poulos (1998), were utilized for calculation of the maximum surface settlement as presented in Fig. 12(a). Circular tunnel data for maximum surface settlement are presented in Fig. 12(b). As the application of empirical analysis to rectangular tunnel shapes has not yet been established, only circular tunnels were analyzed, and showed a similar alignment to both methods.

4 Parametric study

Key parameters were selected, to study their effects on the settlement and bending moment used in the PLAXIS modeling procedure. These included the mesh size, volume loss, Young's modulus, friction angle, cohesion, and node system utilized in the study. This study was undertaken using only rectangular tunnels, as the previous literature has already considered circular tunnels for the majority of these parameters.

4.1 Effect of volume loss

Volume loss for a tunnel is dependent on site-specific soil conditions. The volume loss is also dependent on the tunneling techniques, level of control during construction, and the stiffness of the tunnel lining system. Typically, for clay, the volume loss is considered as 1.5%–2%, and so 1.5% was adopted as a constant parameter for all models. Volume loss has a direct effect on the settlement over

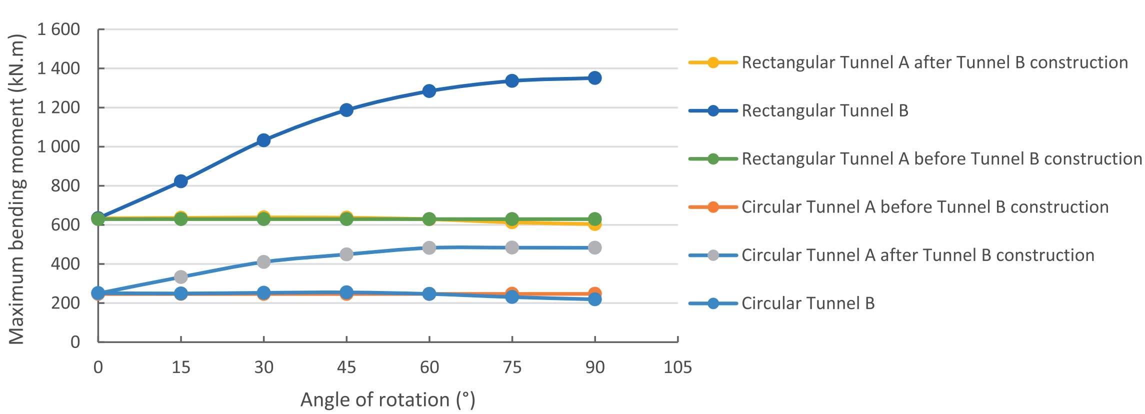


Fig. 10. Effect of relative position on maximum bending moment.

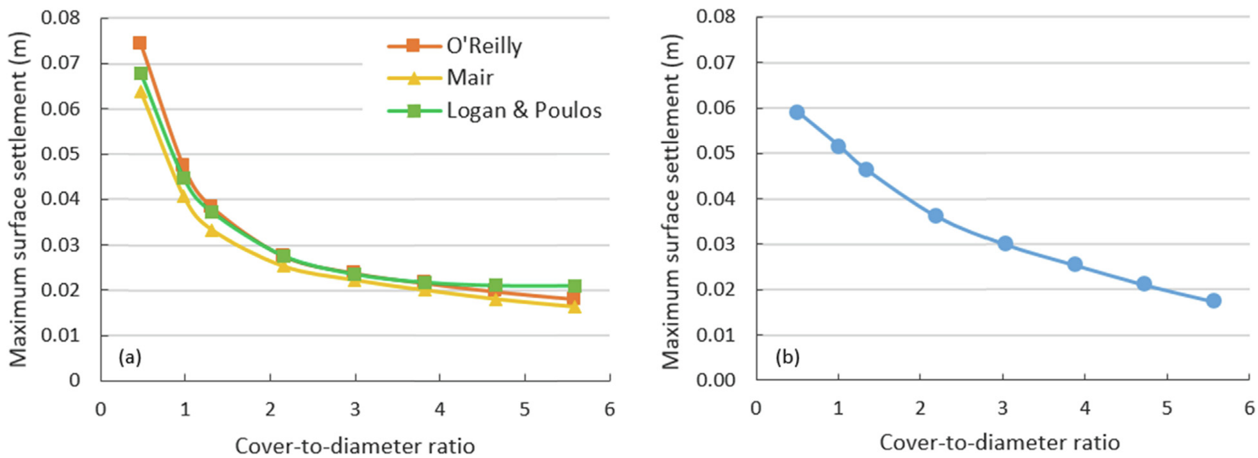


Fig. 12. Effect on circular tunnel maximum surface settlement (a) Empirical and analytical methods and (b) PLAXIS analysis.

tunnels. As the volume loss increases, the settlement also increases, as depicted in Fig. 13(a). Figure 13(b) demonstrates the effect of varying the volume loss on the moment coefficient. A higher rate of volume loss leads to a higher moment coefficient; this has a greater effect for shallow tunnels. For deep tunnels, the variation of volume loss only plays a minor role in variation of volume loss.

4.2 Effect of ground Young's modulus

The variation of Young's modulus can theoretically change the type of soil being modeled in PLAXIS. However, the purpose of including this parameter in the parametric study is to determine its level of effect in the modeling procedure. For shallow tunnels, there is a greater effect of Young's Modulus on surface settlement, where higher E values lead to greater surface settlement. For deep tunnels, there are only minor differences in surface settlement, as depicted in Fig. 14(a). As presented in Fig. 14 (b), the variation of Young's modulus has little effect on the moment coefficient, based on the maximum moment produced in the tunnel lining. There is a slightly greater effect of Young's modulus on the deeper tunnels, as the amount of pressure exerted on the tunnel is greater than that at shallow depths. Therefore, the structural deflections of the lining are greater, and the stiffness of the ground is more significant in providing lateral support.

4.3 Effect of soil friction angle

Changing the friction angle is essentially changing the soil type. For clay, this value can range between 0° and 35°. In Fig. 15, for friction angles between 15° and 35°, there is a slight difference in moment and surface settlement in numerical models. For the purpose of this investigation, a value of 25° was used to allow for application to a broader spectrum of clay.

4.4 Effect of cohesion

The effect of cohesion is very small on both surface settlement and moment coefficient. Figure 16 displays the slight variation caused by cohesion. As the cohesion increases, the moment coefficient decreases, and the surface

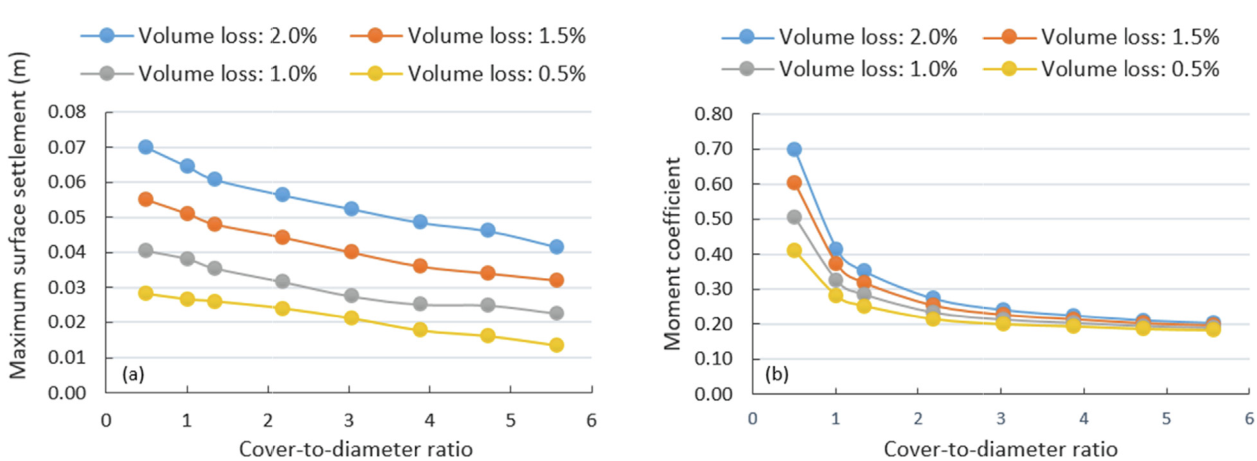


Fig. 13. Effect of volume loss on (a) settlement and (b) moment coefficient.

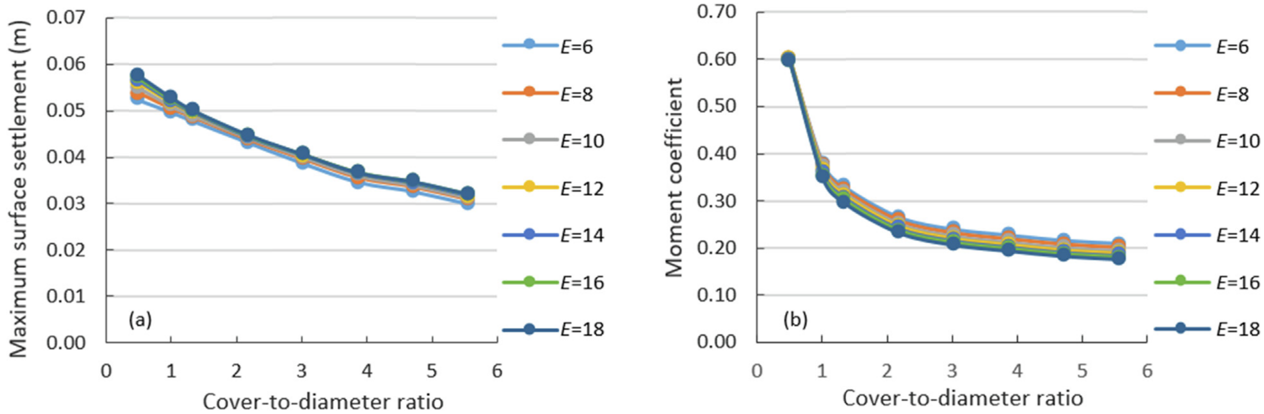


Fig. 14. Effect of Young's modulus on (a) the settlement and (b) the moment coefficient.

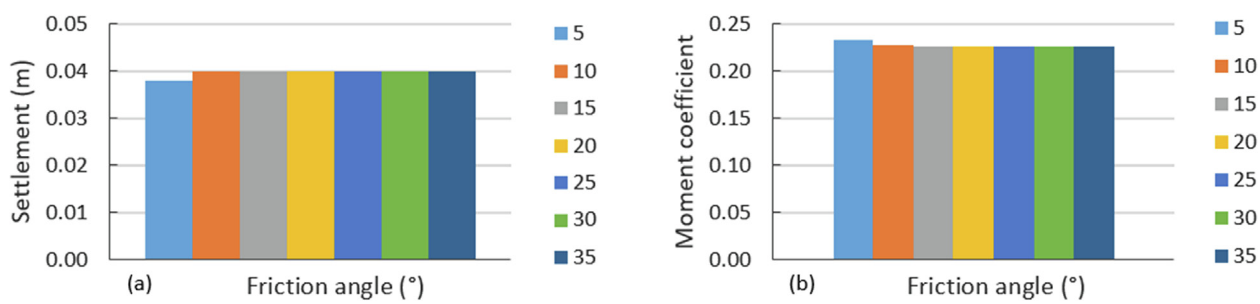


Fig. 15. Effect of friction angle on (a) settlement and (b) moment coefficient.

settlement increases. When the cohesion is higher, the moment coefficient decreases. However, the scale of the graphs exaggerates the effect of cohesion.

5 General discussion

5.1 Cross-sectional area benefits of rectangular tunnel boring machines (TBMs)

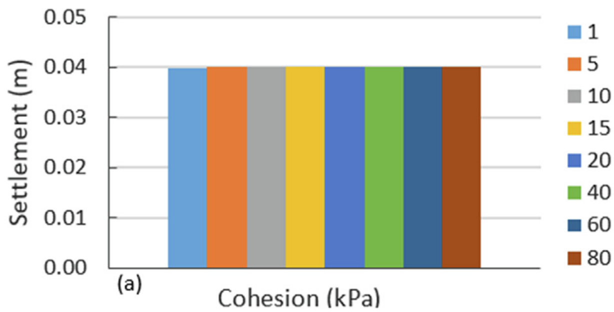
The cross-sectional area of any tunnel is crucial for tunnel design. By following road tunnel design, considerations such as number of lanes, lane shoulders, drainage, and lighting the required tunnel area can be determined. In some circumstances, the minimum cross-sectional area of a rectangular tunnel is less than that of the circular tunnel. Space proofing exercises further to this study would be required to compare the use of tunnel spaces for each tunnel shape. However, for the purposes of comparison, and assuming the lane width and height requirements for both tunnel shapes are the same, a two-lane wide tunnel would be approximately 9 m in width, inclusive of shoulder lanes (1 m each), with each lane being 3.5 m wide and 4.6 m high. The entire cross-sectional area would be:

(1) $\frac{\pi \times D^2}{4} = \frac{\pi \times 9^2}{4} = 63.6\ \text{m}^2$ for a circular tunnel,
(2) $L \times B = 9 \times 4.6 = 41.4\ \text{m}^2$ for a rectangular tunnel.

In that regard, strictly, the circular shape would need a slightly larger diameter to provide the required 9 m width over a height of 4.6 m. Even without this adjustment, the difference in volume per meter run of the tunnel is 22.2 m^3. For excavation, the thickness of the lining should also be included. In terms of processing this material, and the removal from the tunnel and the admixtures required, this is considered as an unnecessary waste of tunneling machinery. In road tunnels, a significant portion of the space within circular tunnels is often not used efficiently. The services for a rectangular tunnel can be accommodated within the interior cross-sectional area of the tunnel without adding significant space outside the traffic envelope, as demonstrated by the Hongzhuan Road underpass tunnel.

It is difficult to compare the advance rate of a rectangular TBM to a circular TBM because of limited data, as the soil conditions must be same to create a valid basis for comparison. Generally, circular TBM advance rates have been researched more and have a larger availability of data, so their advance rates are typically higher than those in the one case study found for the use of the rectangular TBM.

The reduction in the volume of muck removed from the tunnel is considered a major advantage of the rectangular tunnel shape. The advance rate of the rectangular TBM requires more research, rather than relying on one case study for a comparison to the advance rate of a circular TBM. Although the cross-sectional area for rectangular tunnels is less than circular tunnels, the moment produced is significantly higher. Based on the findings of this study, rectangular tunnels might require three times the reinforcement of a circular tunnel. This would be a major consideration in selecting the shape of the tunnel.



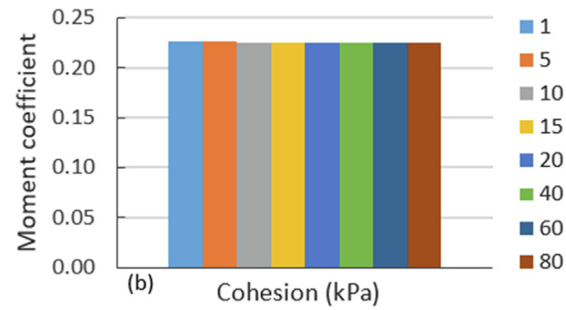


Fig. 16. Effect of cohesion on (a) settlement and (b) moment coefficient.

5.2 Rectangular TBMs vs traditional jacking methods

An assessment of constraints, costs, programs, and construction risks dictates the choice of excavation technique. It is difficult to accurately estimate the generic costs of tunnel construction, as they rely on a number of factors, particularly soil geology and tunnel length. Investigation into this aspect of tunneling requires further research and data collection; however, the high variation in implementation factors limits an accurate conclusion of tunnel cost. Generally, the cost of each method can be roughly estimated as:

(1) Cheaper for traditional very shallow depths and short tunnel lengths;
(2) Expensive for sourcing, establishing, launching, and servicing a TBM, but usually, the greater efficiency of excavation achieved once the TBM is established is worthwhile.

The production rates of each tunneling method are another aspect that determines the choice of construction. The general advance rates for each tunnel method in soft soil are:

(1) Rectangular TBMs: 4–6 m per day (CREG, 2016),
(2) Jacked box tunnel: 4–7 m per day (Najafi, 2010).

Generally, a tunnel type is selected depending on the constraints and length of construction. A summary of the advantages and disadvantages of tunnel jacking and TBM is presented in Table 2. Cut and cover tunnels are usually the preferred option for short lengths at shallow depths. Jacking is required where overhead infrastructure cannot be disturbed, similar to the case with a rectangular TBM. The main difference between a preference for tunnel jacking and a TBM is the length of the tunnel and the control in direction. Rectangular TBMs are a form of a special case of box jacking, where instead of jacking with excavation equipment (excavator, front-end loader, etc.), a TBM at the tunnel face does the excavation. The TBM has greater control and efficiency for longer tunnels. Generally, jacking is only used for tunnels with limited length.

The selection of the right tunneling method for the right purpose is project-dependent. Rectangular TBM technology is still relatively new, so awareness of this technology may lead to better performance in the field over tunnel jacking and cut and cover methods.

5.3 Future studies

Further investigations that can be considered based on the findings of this study include:

(1) Adding loading to surface and internal tunnel loading and assessing effect on bending moment and settlement,
(2) Analysis of the findings of this report with 3D PLAXIS software or any other 3D finite element analysis program,

Table 2
Advantages and disadvantages of rectangular tunnel excavation techniques.

	Rectangular tunnel boring machine (TBM) – special jacking case	Jacking method – box tunnels
Advantages	Able to control TBM deviation accurately Provide support of the excavation face Suitable for construction under water table (if face sealed) Limited disruption to surface i.e., only initial excavation required to lower TBM into launch position	Efficient for short length tunnels at shallow depths (where open cut is not an option) Limited disruption to surface i.e., only initial excavation required to allow jacking system into place
Disadvantages	Expensive TBM Soft soil only Efficient for long tunnel lengths May require other tunnel types at tunnel portals leading to increased cost	Limited control of jacking direction Only useful for short tunnel lengths Soft soil only May require multiple plants to excavate tunnel face efficiently

(3) Investigation on how to minimize the moment produced in a rectangular tunnel by possibly changing the shape to allow for an arched roof,
(4) Creating a cost vs benefit analysis of rectangular TBMs against conventional tunneling techniques to assess the implementation of this technology, and
(5) Undertaking tunnel space proofing to compare the efficiency of rectangular tunnel space for various uses.

6 Conclusions

This paper describes an investigation into the viability of rectangular TBMs as an alternative to the traditional circular TBM. PLAXIS 2D was utilized to determine the surface settlements and maximum bending moments in the tunnel lining produced in both tunnel shapes, with variation in the depth of burial, relative positions, critical distance, and tunnel size. Key conclusions from this investigation include:

(1) Depth of burial
   (i) Settlement for rectangular tunnels is slightly less than that for circular tunnels, for shallow depths with a smaller range of settlement values directly above the twin tunnels. The surface settlement range for twin rectangular tunnels is also less than twin circular tunnels. These results might be affected by maintaining a single tunnel-lining thickness for all tunnel depths.
   (ii) Circular tunnels have less settlement than rectangular tunnels for deep tunnels.

(2) Relative positions
   (i) Tunnels at the same level have lower settlement than piggyback tunnels for rectangular tunnel shapes.
   (ii) Piggyback tunnels have increased moments in the tunnel constructed secondly, as compared with the tunnel at the same level.

(3) Tunnel size
As the size (diameter) of the twin tunnels increases, the settlement and the moment coefficient increase for both tunnel shapes.

(4) Critical distance
   (i) The critical distance of circular and rectangular tunnels is approximately 2.5*d* (center to center), distances closer than 2.5*d* will result in significant increase in the moment coefficient.
   (ii) Rectangular tunnels spaced at distances closer than 5*d* cause an increase in settlement.
   (iii) Circular tunnels spaced at distances closer than 2.5*d*–3*d* cause an increase in settlement.

The PLAXIS modeling indicates that shallow depth tunnel construction in soft soil by a rectangular TBM produces less settlement than circular tunnels. However, the bending moment produced in the rectangular tunnel lining is higher than that for circular tunnel shapes. The smaller cross-sectional area of excavation for rectangular tunnels reduces costs associated with muck removal. Tunnel design engineers should consider this new rectangular TBM technology for use in future shallow depth tunneling projects. It is worth mentioning that some conclusions are sensitive to some of the assumptions, such as volume loss modeling.

Conflict of interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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