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DEPENDENCE OF TUNNEL DEFORMATION DUE TO ADJACENT PILE UNDER LOADING ON TUNNEL GEOMETRY

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ABSTRACT: With rapid urbanization, large number of tunnels with various dimensions have been constructed for transportation and utility systems in many big cities. At the same time, the constructions of infrastructures using a pile foundation system are also necessary in urban area. With limited space, the existing tunnels can be inevitably impacted by the newly constructed pile-supported structures. With various design criteria of tunnel lining, the size and thickness are varied from project to project. With an adjacent pile under loading, different degrees of impact on these tunnels are expected. This study numerically investigates the effect of tunnel diameter and lining thickness on tunnel deformation due to adjacent pile under loading. The MRTA and WMA tunnels in Bangkok subsoil are chosen as the reference cases for investigation. From a series of parametric study, a relationship between the tunnel deformation and dimensionless parameter, which include the size and thickness of lining, can be successfully established.

Keywords: Existing tunnel, Tunnel size, Lining thickness, Out-of-roundness, Pile under loading, Numerical analysis

1. INTRODUCTION

To deal with the problem of limited space in major cities, large number of tunnels, e.g. transportation tunnels, electricity tunnels and water supply tunnels, have been constructed for transportation and utility systems. At the same time, more new infrastructures are also constructed in these urban areas, e.g. flyovers and tall buildings, all of which require pile foundation. The piles of these new structures are inevitably close to existing tunnels as shown in Fig. 1.

Several previous studies [1-5] reveal that the piles under loading can induce the change of stress state and deformation of surrounding soils resulting to an impact on existing tunnels. An assessment on the stability and integrity of the tunnels due to the impact of piles under loading is thus essential. Although different assessment methods in terms of tunnel deformation are considered in the previous researches [1-5], a specific tunnel diameter and thickness were considered in each study. In engineering practice, with various purposes of tunnel utilization, the tunnel diameter (*D*) and lining thickness (*t*) are varied. Bakker and Blom [6] investigated the parameters to get the most economic tunnel design by using analytical method, the study indicates that the ratio between lining thickness and tunnel diameter (*t*/*D*) is the key design parameter and has strong influence on a tunnel deformation.

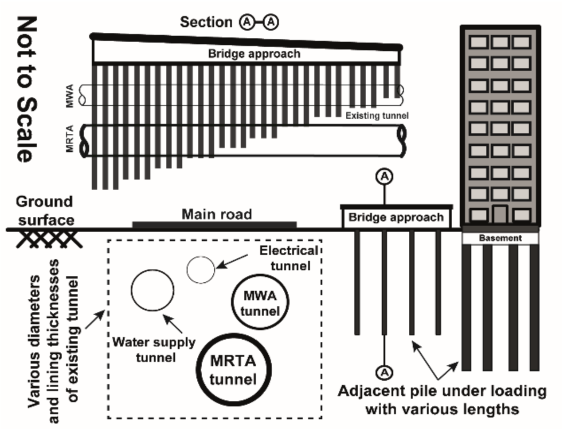

Fig. 1 newly structures constructed to adjacent existing tunnels.

Therefore, the effect of tunnel size and lining thickness on the tunnel deformation due to adjacent pile under loading are investigated by finite element method (FEM) in this study. The Mass Rapid Transit Authority (MRTA) Blue Line extension project and Metropolitan Waterworks Authority (MWA) tunnels in Bangkok subsoil are chosen as the reference cases for the investigation. From a series of parametric study, a simple relationship between the tunnel deformation and dimensionless parameter, which include the diameter and thickness of lining, can be established as a guideline for tunnel assessment due to loaded pile.

2. CHARACTERISTICS OF CASE STUDIES

The characteristics of the MRTA and MWA tunnel projects in Bangkok subsoil with groundwater condition as piezometric drawdown are considered to investigate the effect of tunnel diameter and lining thickness on tunnel deformation due to loaded pile as depicted in Fig. 2a. The MRTA and MWA tunnels having outer diameters of 6.30 m and 4.07 m, lining thicknesses of 0.30 m and 0.15 respectively, are located at the depth, L_T, of 20 m below the ground surface. The Bangkok subsoil based on the actual tunnel alignment of those projects where the tunnel located in stiff clay is considered. While, a tunnel in the soft clay referred to as the tunnel transition section, is also considered in this study. The elevations of pile tip with respect to the spring line level considered and the clearances normalized by the outer tunnel diameter (D) are also shown in Fig. 2 b.

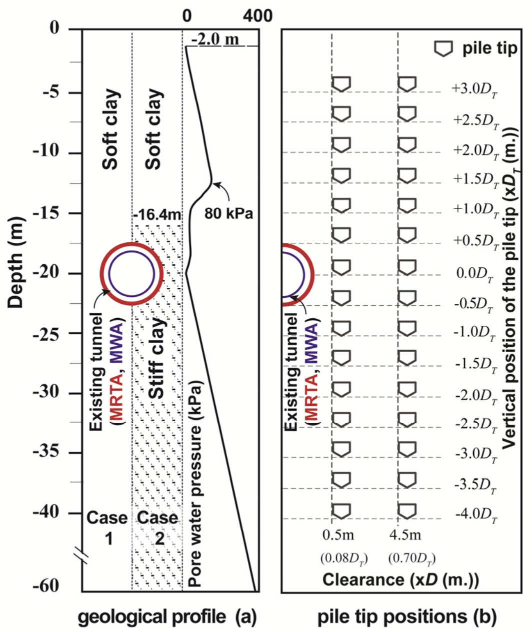

Fig. 2 Illustration of geological profile (a) and pile tip positions (b) considered in this study.

3. ANALYSIS METHOD

The FE analysis consists of two parts. The primary investigation of the effects of size and thickness of tunnel lining on tunnel deformation due to loaded pile are firstly performed by 3D-FEM. The parametric analysis, where various diameters and thicknesses of lining are considered, is conducted to establish a relationship between the tunnel deformation and dimensionless parameter in terms of a simple equation. The details of analysis method are described in the subsequent sections.

3.1 Finite Element Model

3.1.1 Mesh

An example of 3D FE mesh, the tunnel constructed in stiff clay, indicating the relevant geometry, soil profile and element discretization is illustrated in Fig. 3. To simulate a tunnelling problem in three-dimensional model, the FE model is sufficiently extended to avoid the boundary effect. From previous study [7], a distance of 4.0 D in lateral and longitudinal directions from the centre of FE model are sufficient. Thus, the meshed domain had an extent of 60 m (≈9.5 D) in the vertical and longitudinal directions and 80 m (≈12.5 D) in the transverse direction.

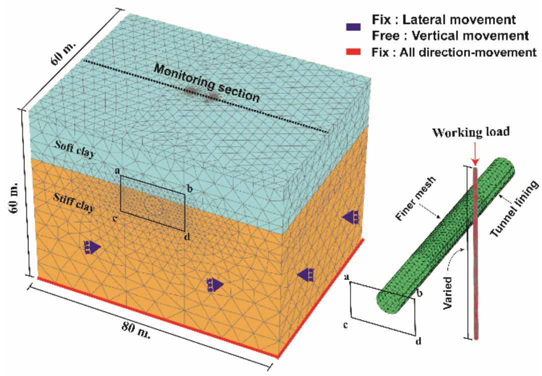

Fig. 3 Example of finite element mesh for the tunnel constructed in stiff clay.

The monitoring section was defined at the centre of longitudinal direction. The soil stratum and bored pile were discretized into the 10-node tetrahedral elements or volume elements. The 6-node triangular plate elements were used to simulate the tunnel lining. The finer discretization mesh with suitable aspect ratio was used to accommodate the accuracy of the solutions, especially in the zone between pile and tunnel. The PLAXIS version 2013 software was implemented for mesh generation and analysis [8].

3.1.2 Analysis condition

For initial stress state, the vertical and horizontal effective stresses were determined by given unit weight of soil and coefficient of static earth pressure, K_0, for all strata. The pore water pressure was also generated by giving piezometric drawdown condition. The undrained analysis was considered.

In order to control the displacement boundary condition, the horizontal movement were restricted but allowed for vertical movements at the lateral boundaries of the mesh. The bottom boundary of the mesh is fixed (no vertical and horizontal movements). These conditions were applied to all finite element models throughout the study.

3.1.3 Material properties

The concrete lining and bored pile were assumed to be a linear elastic as shown in Table 1. The value of interface friction)R_{inter}(between the surrounding soil and structural elements)EPB, tunnel lining or bored piles(was chosen to be 0.9 in the study

The Hardening Soil (HS) model which is successfully employed in simulation of various kinds of geotechnical works in sot ground [9-12] is adopted. The HS model parameters as presented in Table 2 were mainly calibrated from laboratory testing results of soil samples together with the field measurement conducted by Prust [13]. The parameters have been used to analyse the tunnel work in Bangkok [5], [14].

Table 1 Material properties of the bore pile and tunnel lining [14].

	Young modulus [*E*] (kN/m^2)	**Poisson's ratio** [υ]	**Unit weight** [γ] (kN/m^3)
Tunnel lining Bored pile	31 x 10^6	0.20	24

Table 1 Soil model parameters [5], [14], [15]

Soil layer	**Soft clay**	**Stiff clay**
Material model	Hardening Soils (HS model)	
E_{oed}^{ref} (kPa)	5,000	63,158
E_{50}^{ref} (kPa)	5,000	63,158
E_{ur}^{ref} (kPa)	15,000	189,474
γ_{sat} (kN/m^3)	16	18
υ_{ur} (-)	0.2	0.2
ϕ' (°)	22	22
c' (kPa)	5	18
m (-)	1	1
p_{ref} (kPa)	100	100

3.2. Analysis Process

The simulation process, which is carried out by 3D FEA, is divided into two stages. The tunnelling process with the Earth Pressure Balance (EPB) shield method is simulated by following the method proposed by Lueprasert [16]. The tunnelling process was verified by comparing, measured surface settlement of MRTA and the structural forces of previous researches [17 - 18]. The second stage is to assess the tunnel deformation due to the application of the axial load to the single pile modelled as wished-in-place. The applied load is the predetermined working load based on the alpha method [19]. The tunnel deformation is assessed by using the method proposed by Lueprasert [5] as shown in Fig. 4.

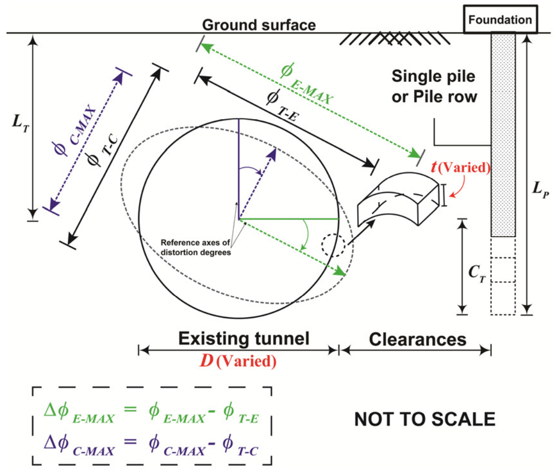

Fig. 4 The schematic of the assessment method in terms of the maximum changes in tunnel diameter.

The figure shows the assessment method used to trace the maximum tunnel deformation due to adjacent loaded pile located on single side of the existing tunnel. The assessment method in terms of the maximum extension change ($\Delta\phi_{E-MAX}$) and the maximum contraction change ($\Delta\phi_{C-MAX}$) are denoted the largest changes in tunnel diameters due to effects of pile under loading as widening and shortening behaviour respectively. The tunnel diameter and lining thickness are varied to assess the maximum changes in tunnel diameter. Note that only the deformation due to an adjacent pile under loading is considered; that due to the excavation process is not included.

The second part is to establish a relationship between the tunnel deformation in terms of the maximum changes in tunnel diameter and dimensionless parameters from a series of parametric study conducted by 2D FEA. The effect of adjacent row pile on the existing tunnel, which can be more serious than that of single pile in engineering practice, is investigated. Various lining thicknesses and tunnel diameters as tunnel ratio, (lining thickness to tunnel diameter *t*/*D*) are modelled to analyse the relationship of various tunnel ratios and tunnel deformation. Generally, with conservative design of tunnel lining, the ratio of lining thickness to tunnel diameter can be classified into a thick shell structure. However, from the previous study [20], the results indicate that either thin or thick shell element can give a reasonably accurate distortion of cylindrical tubes. Thus, the thin shell structure formulated in PLAXIS code, is adopted to model the tunnel lining in this study.

4. ANALYSIS RESULTS

The analysis results are comprised of two parts: the first one is the investigation of the effects of adjacent pile under loading on the maximum change in tunnel diameter, $\Delta\phi_{E\text{-}MAX}$ or $\Delta\phi_{C\text{-}MAX}$, of different tunnel diameters based on MRTA and MWA projects. For the second part, the relationship between the out-of-roundness and dimensionless parameters is carried out to establish the relevant equation and the chart indicating the effects of loaded pile on allowable tunnel deformations referred from Land and Transport Authority (LTA) code [21].

4.1 Investigation of Effect of Tunnel Diameter and Lining Thickness on Maximum Change in Tunnel Diameter

4.1.1 Different tunnel diameters

The lining thickness of 0.30 based on MRTA tunnel are fixed while the tunnel diameters of 4.07 and 6.30 m, which referred to MWA and MRTA tunnel diameters respectively, are modelled to investigate the impact of the adjacent bored pile under loading.

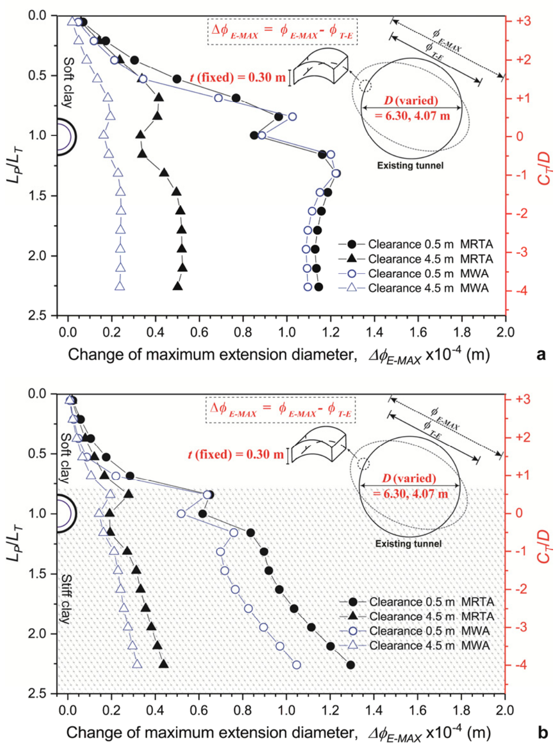

Fig. 5 The maximum extension changes of tunnel diameter due to pile under loading for different tunnel diameters. (a) for a tunnel located in soft clay, (b) for a tunnel located in stiff clay

Because the previous research [5] reveals that both the trend and magnitude of $\Delta\phi_{E\text{-}MAX}$ and $\Delta\phi_{C\text{-}MAX}$ are almost identical to each other, so only the results for $\Delta\phi_{E\text{-}MAX}$ are shown herein. $\Delta\phi_{E\text{-}MAX}$ for the tunnel located in soft clay and stiff clay against various normalized pile tip level to tunnel depth (L_P/L_T) and clearance of 0.5 and 4.5 m are illustrated in Figs. 5a and b, respectively. The normalized distance from tunnel spring line to tunnel diameter, C_T/D, are also provided on the right side of the y-axis.

For tunnel located in soft clay (Fig. 5a), $\Delta\phi_{E\text{-}MAX}$ of 6.30 m tunnel is slightly larger than that of 4.07 m tunnel, especially the loaded pile located at clearance of 0.5 m. $\Delta\phi_{E\text{-}MAX}$ increases with increasing L_P when the pile tip is located above the tunnel crown ($C_T/D \geq 0.5$) and becomes decreasing before increasing again. When the pile tip is located below the tunnel invert, -0.5 D, $\Delta\phi_{E\text{-}MAX}$ slightly increases and reaches the maximum value at the pile tip located approximately -1.0 D. When pile tip is located in the range of -2.0 D to -4.0 D, $\Delta\phi_{E\text{-}MAX}$ remains almost constant.

For the case of the tunnel located in stiff clay as shown in Fig 5b, the larger $\Delta\phi_{E\text{-}MAX}$ of 6.30 m tunnel can be clearly observed, especially in the range of pile tip located below tunnel invert. The $\Delta\phi_{E\text{-}MAX}$ are generally smaller than those of tunnel located in soft clay, especially when the pile tip is located in soft clay. When the pile tip is extended into stiff clay (+0.5 D), the $\Delta\phi_{E\text{-}MAX}$ drastically increases because of a larger working load on bored pile.

By considering the constant lining thickness of 0.30 m, the result described above indicates that the tunnel diameter has influence on the tunnel deformation due to nearby loaded pile.

4.1.2 Different lining thicknesses

The distribution patterns of $\Delta\phi_{E\text{-}MAX}$ for both cases are similar to those of $\Delta\phi_{E\text{-}MAX}$ from the previous section (different tunnel diameters) for the same case as shown in Fig. 6. The $\Delta\phi_{E\text{-}MAX}$ of tunnel with the lining thickness of 0.15 m is clearly larger than that with the lining thickness of 0.30 m. This indicates that the lining thickness has an influence on the tunnel deformation due to pile under loading.

Fig.7 shows the maximum extension change in tunnel diameter, $\Delta\phi_{E\text{-}MAX}$, on y-axis against the varied tunnel diameter and lining thickness as shown in Figs.7a and b, respectively, on x-axis. The maximum effect of the loaded pile located at -1.0 D and clearance of 0.5 m on $\Delta\phi_{E\text{-}MAX}$ obtained from the previous section is considered with different tunnel diameters and lining thicknesses.

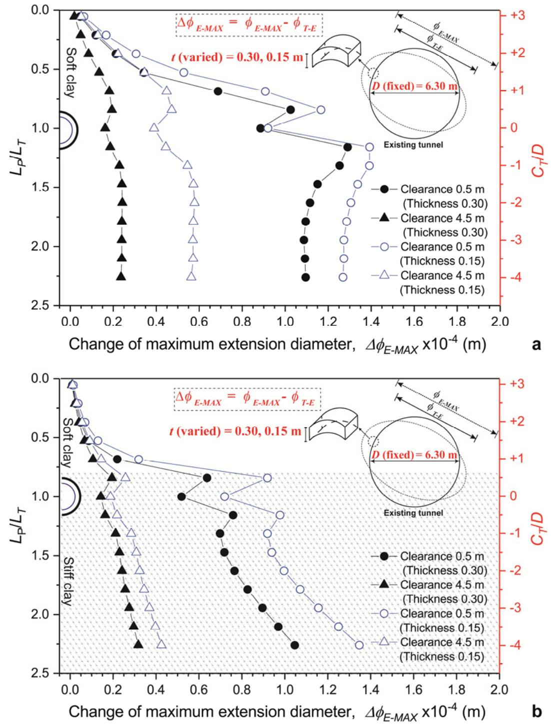

Fig. 6 The maximum extension changes of tunnel diameter due to a pile under loading for different lining thicknesses. (a) for a tunnel located in soft clay, (b) for a tunnel located in stiff clay

For different tunnel diameters (lining thickness of 0.30 m is fixed) as depicted in Fig7a, $\Delta\phi_{E\text{-}MAX}$ increases with increasing tunnel diameter. By considering different tunnel thicknesses (tunnel diameter of 4.07 m is fixed) as depicted in Fig7b, the decreasing of $\Delta\phi_{E\text{-}MAX}$ with increasing lining thickness can be seen. This can evidently confirm that the tunnel diameter and lining thickness parameters have strongly influence on the effects of loaded pile on the tunnel deformation.

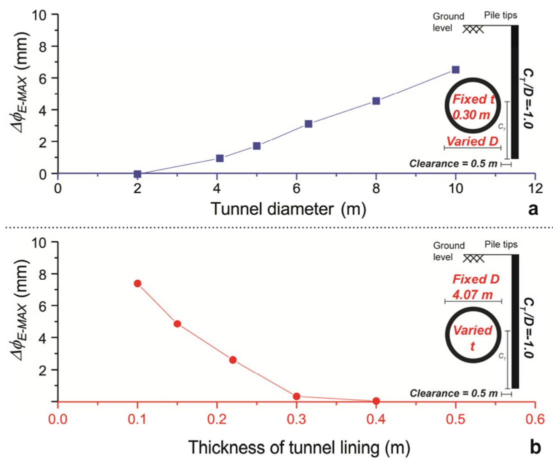

Fig. 7 The effects of different tunnel diameters and lining thicknesses on the maximum extension changes of tunnel diameter.

4.2 Application of Tunnel Deformation in Preliminary Assessment of Tunnels with Various Diameters and Lining Thicknesses

To assess the tunnel deformation in this section, inferring from assessment method of bending strain in surface lining [22] and the principal of circularity shell structures (e.g., pipelines, tanks, and steel lining), the unsymmetrically distortional shapes can be assessed by the percentage of out-of-roundness defined in terms of parameters including the minimum, maximum, and nominal diameters of a distorted structure as shown in Eq. (1) [23].

$$\text{Out-of-roundness (\%)} = \frac{D_{\max} - D_{\min}}{D} \times 100 \qquad (1)$$

Where $D_{\max}$ and $D_{\min}$ denote for the maximum and minimum tunnel diameters after distortion. The dimensionless parameter, which relatively involves with the lining thickness (t) and the tunnel diameter (D), is established from the moment of inertia of tunnel lining and the length of bored pile (L_P). The L_P implies the magnitude of applied axial load of bored pile. The moment of inertia of 1 m wide tunnel lining is $t^3/12$, whereas $\pi D^2/4$ represents the tunnel size. Based on the preliminary investigation, it reveals that the tunnel deformation increases as tunnel size and pile length increase and the thickness decreases. Therefore, the dimensionless parameter is postulated as ratio of lining thickness to tunnel diameter and length of bored pile as t^3/D^2L_P.

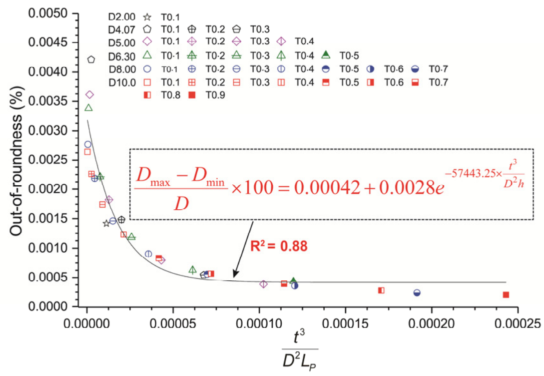

Fig. 8 The relationship between out-of-roundness and influencing factors on the tunnel deformation.

Series of parametric study regarding relative influencing factors on the tunnel deformation due to adjacent bored pile as mentioned above, is conducted using the 2D-FE to synthetically establish the simple equation in this section. The tunnel located in soft clay and pile tip located at -1.0 D and clearance of 0.5 m resulting to the maximum value of tunnel deformation are chosen. The tunnel diameter and lining thickness are varied between 2.0 to 10.0 m and 0.10 to 0.90 m respectively, in the analyses.

Fig. 8 shows the plotted between out-of-roundness and the dimensionless parameters as t^3/D^2L_P. An equation can be obtained by the curve fitting method with the coefficient of determination (R^2) of 0.88 as shown in Eq. 2.

$$\frac{D_{\max} - D_{\min}}{D} \times 100 = 0.00042 + 0.0028e^{-57443.25 \times \frac{t^3}{D^2 L_P}} \quad (2)$$

According to the allowable tunnel deformation of 15 mm for averaged tunnel diameter about 6.40 m regulated by LTA [17], it is postulated herein that the allowable deformation of tunnels with other sizes can be considered so as to keep the ratio of allowable deformation-to-tunnel-diameter constant. By using the Eq.2, tunnel deformation in terms of $D_{\max} - D_{\min}$ for various tunnel diameters and lining thicknesses can be calculated. Together with the allowable tunnel deformation, the chart for estimating the percentage of tunnel deformation can be established as shown in Fig 9. The chart provides the preliminary assessment of the impact for adjacent loaded pile.

The interpretation from the chart using the geometries of MRTA and MWA tunnels reveals that the percentage between maximum possible deformation to allowable value of MRTA tunnel is smaller than that of the MWA tunnel. This is because the serviceability regarding train operation governs the design concept of MRTA. In other words, the MRTA tunnel is safer than the MWA tunnel.

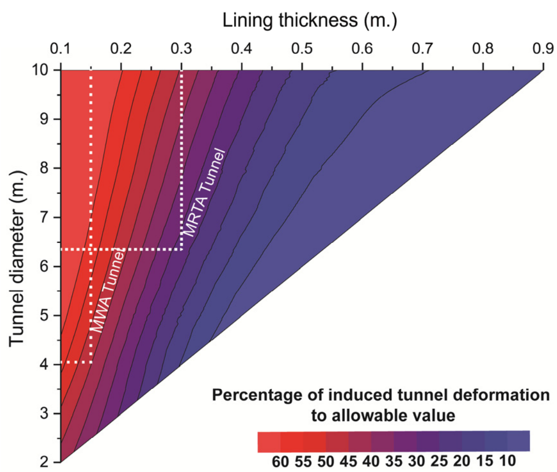

Fig. 9 The assessment chart for tunnels with various tunnel diameters and lining thicknesses.

5. CONCLUSION

The effect of tunnel diameters and lining thickness on tunnel deformation due to adjacent pile under loading is numerically investigated by choosing the MRTA and WMA tunnels in Bangkok subsoil as the reference cases. Series of parametric study regarding relative influencing factors on the tunnel deformation due to adjacent loaded pile, e.g. tunnel diameter, lining thickness, pile length, is conducted. The results can conclude as follows:

1. The tunnel diameter and lining thickness have strong influence on the tunnel deformation due to adjacent loaded pile.
2. The proposed parameters, t^3/D^2L_P, can appropriately capture the tunnel deformation in terms of out-of-roundness due to adjacent loaded pile for various tunnel diameters and thicknesses.
3. With a certain criterion, it is possible to establish a chart that can be used to assess the degree of the tunnel deformation due to adjacent pile under loading for the existing tunnel with various diameters and lining thicknesses.

6. ACKNOWLEDGEMENTS

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