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Investigation on pile behavior in proximity to excavation damage zone (EDZ) induced by TBM excavation

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ABSTRACT

As urban areas are at the peak of its development, overlapping of underground structures and pile foundations are considered as a rising issue. Moreover, due to the noise and vibration of conventional tunneling method, substitution to mechanized tunneling method (TBM) is required to carry out safe and stable underground space development. However, to date, the behavior of pile foundation under mechanized tunneling induced disturbance has not been properly investigated or studied. In this study, the changes in pile foundation behavior in proximity to TBM tunneling induced ground damage will be analyzed by applying rigorous numerical approach, which was verified to simulate the TBM excavation process, and the damages done on surrounding grounds. Based on the results, the damage during excavation had a significant effect on the pile stability with increased proximity.

1. INTRODUCTION

In major urban areas, underground space development has become essential in the field of transportation, commercial and various lifelines (water, electric, gas, etc.). However, the application of conventional drill-and-blast tunneling method in urban areas is not viable due to the noise and vibration during excavation. The noise can cause various lawsuits towards the construction project, which will increase the financial burden to the companies, as well as delay the time schedule of the project. Moreover, the vibration during excavation may cause multiple negative effect on surrounding structure, residence, and other geotechnical matter.

Substitution of the conventional tunneling method to mechanized tunneling method is one of the movements to overcome the limitations in underground space development in urban areas. However, compared to the studies conducted on the structural stability of tunnels excavated under conventional tunneling method, studies on the structural stability or behavior of tunnels excavated based on mechanized tunneling method (e.g. TBM) has not been carried out on an equal degree.

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Numerous institutes studied and investigated the response of the ground around the excavation surface, and on the changes in physical and material properties (Bauer et al., 1996; Emsley et al., 1997; Martin et al., 1997; Read et al., 1998; Kwon et al., 2009). The damage induced in the surrounding ground, i.e. excavation damage zone (EDZ), is found to be critical to the stability of the tunnel during and after the excavation due to the changes, mainly deterioration, in physical and mechanical property compared to the original rock mass (Stepansson et al., 2008; Arson and Gatmiri, 2012; Siren, 2015). The blast vibration caused by conventional drill and blast method (e.g. the New Austrian Tunneling Method; NATM), as well as the vibration due to the advancement of the TBM are found to cause severe damage to the ground which will reduce the strength and stability of the ground and the tunnel (Siren, 2015).

Although numerous studies were carried out on the EDZ and its characteristics, most of the studies and field measurements were focusing on conventional drill and blast method. On the contrast, very few studies were on mechanized tunnels, and attempts to predict the distribution and the range of the EDZ based on numerical analysis or its effect on the structural stability of nearby structures were not actively carried out (Read et al., 1998; Carbonell et al., 2010; Xu and Arson, 2014; Lee et al., 2016).

In this study, the behavioral response of pile foundations in proximity to the excavation damage zone (EDZ) formed from a mechanized (TBM) tunneling. The response of the piles will be numerically analyzed by using a large deformation analysis method. After numerically simulating the TBM excavation process near a pile structure, the damage on the surrounding ground will be computed along with the changes in pile's settlement and lateral movements.

2. DAMAGE ON THE GROUND DUE TO EXCAVATION

Changes in stress distribution around the tunnel occur and due to this fractures and cracks form in the rock mass during excavation. The definition associated with damage zones caused by excavation are summarized in Fig. 1 (Perras and Diederichs, 2016). Harrison and Hudson (2000) use the terminology of construction damage zone (CDZ), where an inevitable excavation consequences and additional effects occur due to excavation. Zone where it undergoes inevitable damages caused by the result of geometry, structure, and/or induced stress changes (i.e independent of excavation method) can be defined as the highly damaged zone (HDZ). Outside the HDZ is normally called the excavation damaged zone (EDZ). The definition of EDZ usually refers to as an area or zone around the excavation surface, where the changes in stress due to excavation exceeds the elastic limit and newly formed fractures or cracks occur. EDZ appears as the tunnel excavates by cracking the rock mass, and this causes irreversible reduction of strength and stability of surrounding grounds (Martino et al., 2007; Jonsson et al., 2009). Siren et al. (2015) introduced a concept of excavation influence zone (EIZ), or excavation disturbed zone (EdZ), where it only involves elastic changes degree of stress redistribution, thus assumed as a reversible change.

The development of the EDZ around the tunnel excavation surface is critical to the stability during tunnel construction process and the tunnel structure after the completion. Diederichs et al. (2004) conducted experiments to define the crack initiation of various

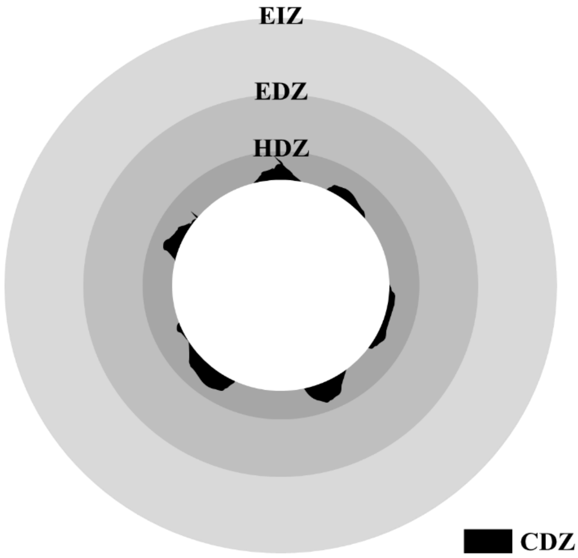


Fig. 1 Various excavation damage zones

rock types, Martin et al. (1993, 2001) suggested a simple equation (Eq. (1)) that under axial loading condition the crack initiation stress is approximately 30 - 40% of the rocks' uniaxial compression strength based on the field stress ratio results (Fig. 2).

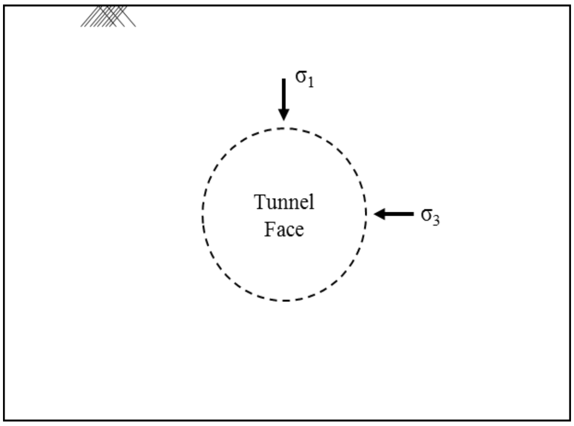
$$\sigma_1' - \sigma_3' = \sigma_{ci} = 30 - 40\% \text{ of } UCS \qquad (1)$$

where, σ_{ci} is the crack initiation stress. Based on the equation (1), this study has defined the EDZ as an area where the deviatoric stress ($\sigma_1' - \sigma_3'$) caused by the excavation and the dynamic load due to vibration exceeds 30% of the ground's uniaxial compressive strength. This is the lower boundary of the definition of the crack initiation stress based on the field stress ratio, and yield larger EDZ around the excavation surface, thus allowing a safer tunnel design and maintenance. As the tunnel excavation is in progress, the initial stress (σ_1 or σ_3) around the excavation surface changes ($\sigma_1 + \Delta\sigma$). As the excavation continues, the deviatoric stress ($\Delta\sigma$) increases. In this study assumption is made that, when the deviatoric stress exceeds 30% of the original rocks' uniaxial compression strength, new cracks are formed, thus EDZ appears around the tunnel excavation surface. By using large deformation analysis, the range and the distribution shape of the EDZ under various conditions are investigated.

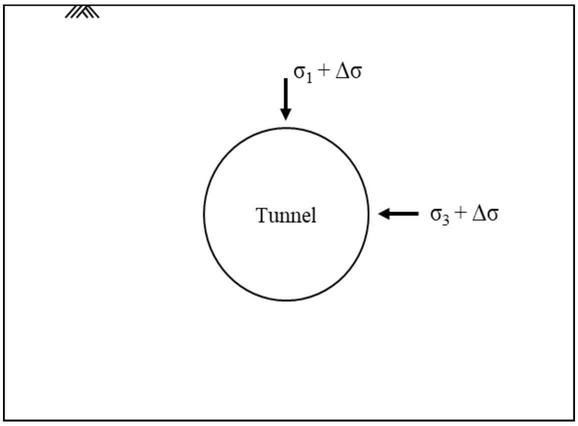
3. NUMERICAL ANALYSIS

3.1 Mesh and boundary conditions

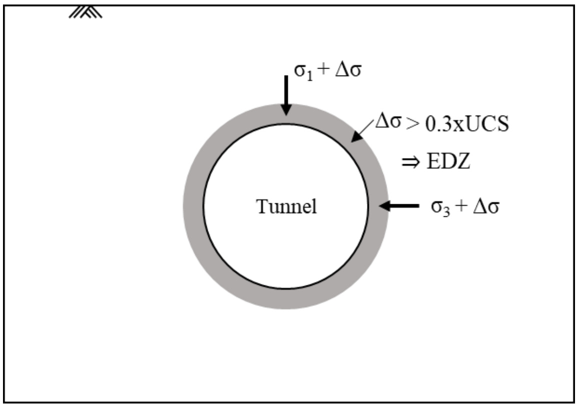
In finite element analysis, the plasticity of soil is considered through constitutive model, and the most common constitutive model for rock is Mohr-Coulomb model and



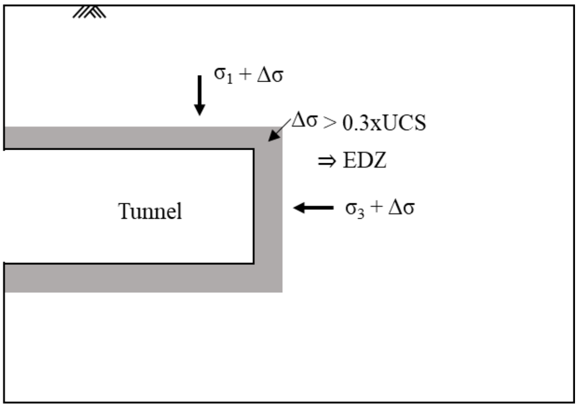
(a) Before excavation



(b) Stress redistribution during excavation



(c) EDZ (front view)



(d) EDZ (side view)

Fig. 2 Schematic of the EDZ due to tunnel excavation

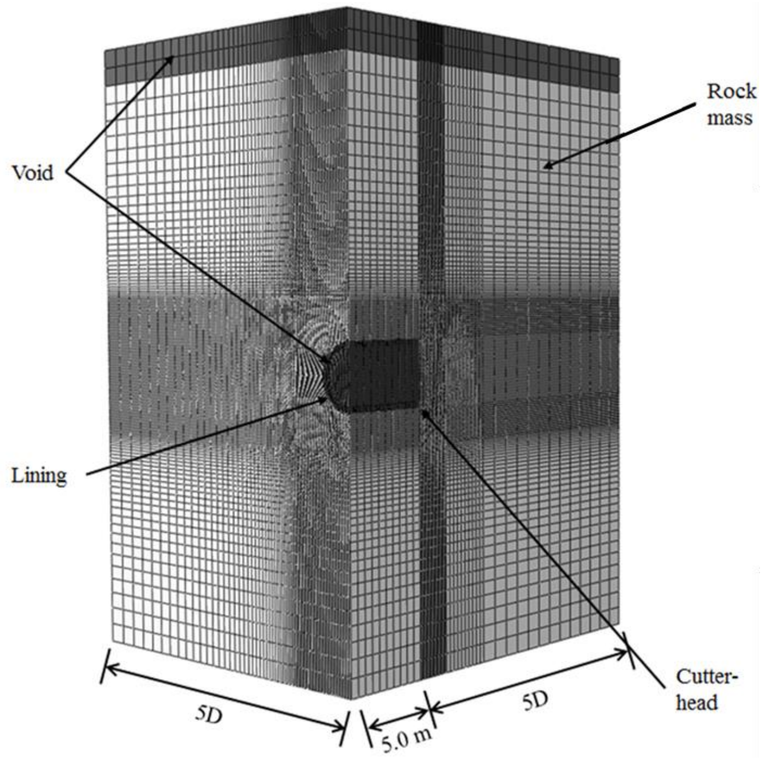
the Hoek-Brown model. In this study, the Mohr-Coulomb model was used to analyze the behavior of rocks for both analytical approaches. The element type for the CEL mesh is set to Eulerian element (EC3D8R).

The interface between the Eulerian and Lagrangian elements for CEL analysis are commonly modelled as a general contact. In this study, the interface between the elements (cutterhead or lining with the rock mass) are modelled as a general contact. The friction coefficient between the elements are set to 0.7, based on previous studies (Gehring, 1996; Zhao et al., 2012; Ramoni and Anagnostou, 2011).

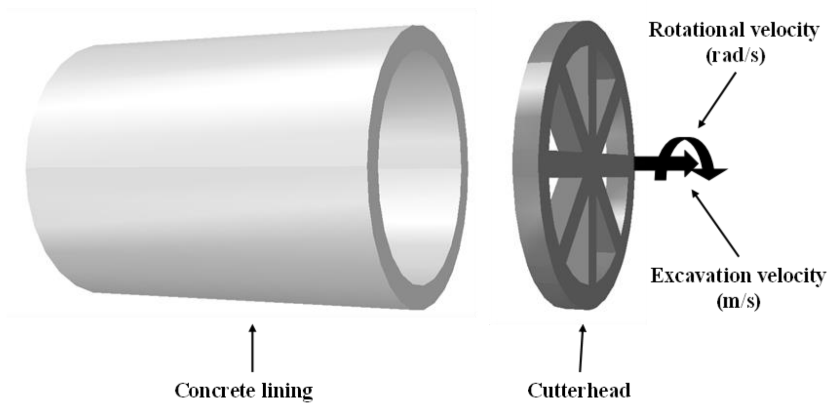
The size of the mesh boundary was modeled to prevent the boundary disturbance effect. Fig. 3(a) shows the mesh of the ground being excavated. The material properties of the rock based on RMR ratings are summarized in Table 1 (Kim, 2021).

3.2 TBM modeling

The modeling of the tunnel boring machine (TBM), which consists of the cutterhead and the lining, is based on a Lagrangian framework for both CEL and auto RITSS analysis. The properties of the TBM are stated in Table 2. The TBM elements are modeled as an 8-node Lagragian brick element (C3D8R) linear elastic material. Initial tunnel length is set to 5m, and the initial geostatic conditions are set accordingly. Fig. 3(b)



(a) FE mesh



(b) TBM cutterhead and lining

Fig. 3 Schematic of the modeling of TBM elements and FE mesh

shows the TBM cutterhead and lining modeled in Lagrangian element.

3.3 EDZ and pile behavior

The EDZ caused during TBM excavation is based on a continuous simulation of TBM advance through the ground mesh (Kim, 2021). The tip of the pile will be placed within the HDZ, EDZ, EIZ and right outside the EIZ. The HDZ, EDZ and EIZ was defined

Table 1. Material property of ground (rock) based on RMR ratings (Jeong et al., 2014)

Group	RMR	E (MPa)	UCS (MPa)	*v*	γ (kN/m3)	*φ* (°)	c (kPa)
I	80~100	20,000	75	0.2	27	45	4,000
II	61~80	10,000	50	0.22	26	40	2,000
III	41~60	6,000	30	0.24	25	35	1,000
IV	21~40	2,000	10	0.26	23	32	400
V	< 20	800	4	0.28	22	30	100
Weathered Rock	-	200	2	0.30	21	32	50

Table 2. Material property of cutterhead and lining

	Model (Element)	E (MPa)	*v*	γ (kN/m^3)	*φ* (°)	*c* (kPa)
Lining	Linear elastic (C3D8R)	23,000	0.15	24.0	-	-
Cutterhead		200,000	0.30	82.5	-	-

as a range where the stress redistribution due to excavation is 50% of the original rock mass' uniaxial compression strength, 30%, and less than 15%, respectively. The CDZ will be not considered in the numerical computation since the size of the CDZ is very small, and it is also incapable of stabilizing or support a pile structure. The numerical analysis will be carried out as the pile placed over, as well as in front of the TBM. This is shown in Fig. 4.

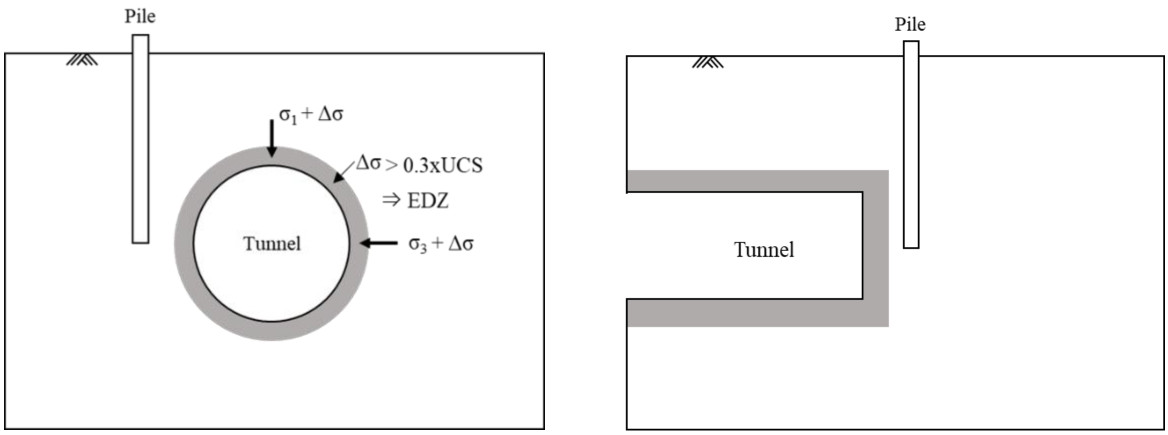


Fig. 4 Assessment of tunnel stability based on deformation

4. CHANGES IN PILE BEHAVIOR ASSOCIATED WITH EDZ

Based on the computed results and rigorous analysis, it can be concluded that the EDZ has a significant effect on the behavior of the pile. The settlement of the pile increased as well as the lateral movement of the pile.

It was obvious that the bigger the damage, bigger the changes in pile behavior. The increase of settlement compared to an original rock mass, was approximately 41%, 22% and 3% for HDZ, EDZ and EIZ, respectively. However, when the excavation process was removed from the analysis the increase rate of the pile settlement was 31%, 14% and less than 1% for HDZ, EDZ and EIZ, respectively. These results show that the HDZ and EDZ can cause an irreversible damage (deterioration) to the rock mass, while damages within the EIZ range was recovered when the TBM excavation stopped.

Similar tendencies were observed with the lateral movement of the pile near TBM excavation. The pile tends to lean towards the direction of the EDZ. This is due to the fact that the mechanical properties directly connected to the deformation, such as elastic modulus, deteriorated within the EDZ. The lateral movement during TBM excavation, was approximately 18%, 10% and 1.5% of the pile diameter for HDZ, EDZ and EIZ, respectively. However, when the excavation process was removed from the analysis the lateral movement was decreased to 7%, 3% of pile diameter and negligible for HDZ, EDZ and EIZ, respectively. This is also an example that HDZ and EDZ causes irreversible changes in surrounding grounds, while changes within the EIZ range can be reversed when the excavation process is removed.

5. CONCLUSION

In this study, the interaction between TBM excavation process and pile foundation was investigated based on large deformation analysis approach. By modeling a pile structure in which the tip is placed within the HDZ, EDZ and EIZ boundary, the changes in settlement and lateral movements were estimated. Through rigorous numerical assessment and analysis, it was found that the existence of EDZ due to TBM excavation has a significant effect on the nearby pile foundation. Moreover, when the ground is damaged over the degree of EDZ (stress redistribution exceeding 30% of original rock mass' uniaxial compression strength) the changes, or deterioration, of the mechanical properties of the rock mass is irreversible. On the contrary, the effect of EIZ on pile movement was found to be insignificant and can be reversed when the excavation process is terminated.

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