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Precutting of Tunnel Perimeter for Reducing Blasting-Induced Vibration and Damaged Zone – Numerical Analysis

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Abstract

Cost-effective tunnel excavation can be achieved with the blasting method. Unfortunately, blasting technique brings with it blasting-induced vibration and noise, which can cause critical social problems such as public complaints. Thus, the development of a novel tunnel excavation method, one that can reduce the blasting-induced vibration, is strongly demanded for the effective management of urban spaces. Thus, this study introduces an innovative vibration-reduced excavation method that combines the conventional blasting technique with the precutting process and carries out a feasibility study of the proposed tunnel excavation method using three-dimensional finite element analyses. The micro-scale study focuses on the stopping holes and contour holes while the macro-scale study deals with the case of a real scale tunnel. From the micro-scale analyses, it can be deduced that the proposed method is effective for the reduction of blasting-induced vibration compared to the conventional line-drilling method. From the macro-scale simulation, it is found that the reduction of blasting-induced vibration is independent of the thickness of the precutting free surface but dependent on the depth of the precutting free surface. As the depth of the precutting free surface increases, blasting-induced vibrations as well as the depth of the excavation-damaged zone can be significantly reduced. Vibration energy induced by blasting does not transmit through the free surface and is trapped inside the target tunnel face. Guided blasting waves cause stress concentration at the target face and maximize the blasting efficiency. It is expected that the construction cost will decrease due to a decrease in the number of drilling holes, the weight of the explosive charges, the overbreak space, and the excavation-damaged zone. In particular, the reductions of the overbreak space and excavation-damaged zone enhance the safety of tunnel construction.

Keywords: *vibration reduction, tunnel blasting, numerical analysis, precutting free surface, line-drilling*

1. Introduction

Modern industrialization and economic growth accelerate urbanization. Nowadays, the connection of highly developed metropolitan cities forms a mega city that demands the construction of underground space for the effective use of limited land. Underground spaces have been used for various purposes such as to facilitate effective traffic systems, urban life space, and industrial storage. However, the development of underground space in urban areas brings with it a few problematic factors such as vibration and noise induced by blasting and cracks induced by differential ground settlement. Especially, the drilling and blasting process has been widely used for trenchless tunneling. The propagating detonation pulse induced by the tunnel blasting process significantly decays with respect to the distance from the blasting source. However, some portion of the detonation pressure propagates through the ground in the shape of elastic waves and causes ground vibration.

The blasting process uses various types of explosives to effectively break a rock mass depending on the rock stiffness. Cost-effective tunnel construction can be achieved with the blasting excavation method. However, we cannot avoid blasting-induced vibration and noise, which can cause critical social problems such as public claims (e.g., for structural damage and civil inconvenience). Thus, the development of a novel tunnel excavation method, one that can reduce the blasting-induced vibration, is strongly needed to allow for the effective management of urban spaces. This study introduces an innovative vibration-reduced excavation method that combines the conventional blasting process with a precutting process and carries out a feasibility study of the proposed tunnel excavation method using three-dimensional finite element analyses.

2. New Vibration-Reduced Tunnel Excavation Technique

One of the solutions for reducing blasting-induced vibration is

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to apply an artificial screen to the tunnel perimeter as a barrier against seismic wave propagation. Uysal *et al.* (2008) used empty barrier holes to reduce blasting-induced vibration in open pit mining. Park *et al.* (2009) analyzed the effect of line-drilling using a distinct element method. In particular, line-drilling has been applied to a tunnel perimeter before the blasting process in order to reduce the blasting-induced vibration and to obtain a high-quality excavation line in the conventional tunnel excavation method (i.e., New Austrian Tunneling Method). These reduction methods utilize empty drilling holes in the tunneling direction. Such empty drilling holes may play the role of an artificial barrier against the seismic waves induced by blasting. However, tunnel sections and neighboring ground are still connected even though there are two or more layers of empty drilling holes along the tunnel perimeter. Seismic waves induced by tunnel blasting not only can be reflected and refracted by the empty holes but can still propagate through the connected area. Furthermore, the blasting-induced seismic wave components that has longer wavelengths than the size of the empty hole cannot be filtered out. Therefore, the installation of drilled empty holes along the excavation perimeter may be ineffective for vibration control.

On the other hand, environmentally friendly rock breaking methods have been developed and applied for rock tunneling (Res *et al.*, 2003), including high voltage current (Shao *et al.*, 2010), chemical agents (e.g., CARDOX system; Parsakhoo and Lotfalian, 2009) and soundless cracking agents (Zhongzhe *et al.*, 1988), thermal methods (Dudoladov, 2006), electrohydraulic and hydraulic methods (Chollette *et al.*, 1976), and plasma techniques (Lisitsyn *et al.*, 1999). Although these may provide noiseless and vibration-free rock excavation methods, they delay the construction process and lead to high construction costs due to their inefficient rock excavation rate.

Abrasive waterjet (which shoots water and an abrasive at very high pressure) and laser techniques have been widely used for accurate processing such as the cutting and drilling of engineering materials. Recently, a hydro-demolition waterjet (i.e., a high power waterjet that shoots water at lower pressure but larger working rate) has been attempted as a means of developing a new technology for tunnel excavation purposes (e.g., Jeng *et al.*, 2004). However, full face excavation using such a technique still demands a significant processing time. Instead, such cutting techniques can be used as supportive and auxiliary tools before tunnel blasting practice. Abrasive waterjets and laser technology can be used to create a free surface along the arch tunnel perimeter for an effective blasting process. A combination of a precutting free surface and conventional blasting could lead to an effective excavation method because a free surface along the arch tunnel perimeter can completely separate the neighboring ground from the tunnel section and prevent the propagation of the elastic waves induced by tunnel blasting. Seismic waves do not propagate through a void interface and are reflected at the free surface and entrapped in the internal media (Song and Cho, 2010). Thus, in this study, we consider the establishment of a continuous void along the arch tunnel perimeter as a vibration reduction method and employ an abrasive waterjet technique to create this continuous void along the arch tunnel perimeter.

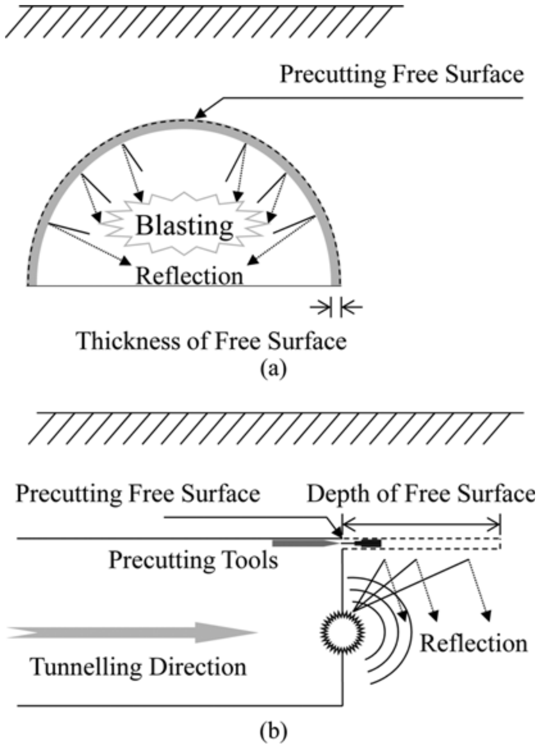

Fig. 1. Tunnel Blasting System with Precutting of Tunnel Perimeter for Reducing Blasting-induced Vibration and Damaged Zone: (a) Transversal View, (b) Longitudinal View

An abrasive waterjet system controls the nozzle pressure, the amount of abrasive contents, and the traversing speed of the nozzle, all of which affect the cutting performance. As can be seen in Fig. 1, the precutting process of a free surface is first performed when the abrasive waterjet system creates a thin continuous arch void with a certain depth along the tunnel perimeter in the tunneling direction; this is followed by the blasting process, in which blasting-induced vibrations are reflected at the continuous void along the tunnel perimeter.

As part of a preliminary study, limited laboratory experimental tests were performed to estimate the feasibility of the abrasive waterjet technique to create a pre-cutting free surface. A water pump, an abrasive feed tank, and a nozzle set were prepared to cut the hard rock specimen with abrasive waterjet as it is presented in Fig. 2(a). The specimen was stiff granite (i.e., uniaxial compressive strength of granite = 196 MPa). A plunger type pump (240 HP) was used to generate the high water pressure. The water pressure and flow rate were kept as a constant values of 245 MPa and 19.2 L/min. To enhance the cutting performance, the 30-40 mesh garnet particles were used as abrasive. The result of pre-cutting free surface obtained from the limited laboratory experimental test is shown in Fig. 2(b). From the test result, it was observed that a clean and continuous pre-cutting free surface is obtained. The cutting depth is measured as 3-5 cm per single cutting. Thus, multiple cutting

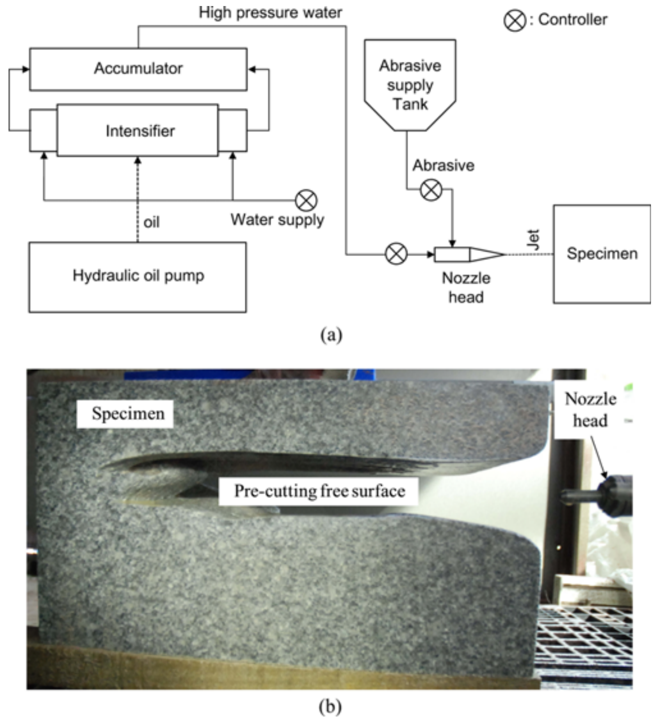

Fig. 2. Feasibility Study with Limited Experimental Test: (a) Test Set Up for Abrasive Waterjet Cutting, (b) Pre-cutting Free Surface

process should be implemented to form the deep pre-cutting free surface.

Cutting process can cause a delay in the tunnel construction process. However, if we increase the number of abrasive waterjet nozzle set to 4 to 5 along the tunnel perimeter, the processing time can be significantly reduced. Also, the cutting efficiency depends on rock physical properties such as hardness, strength, and stiffness. Cutting efficiency of abrasive waterjet can be improved as the strength, stiffness and hardness decrease (Momber and Kovacevic, 1997; Oh and Cho, 2012). Thus, as the stiffness (or hardness) of the rock decreases, the applicability of this proposed method will be expanded. Therefore, the proposed tunnel blasting method may be practically applied to tunneling sites without a delay in the construction process.

3. Numerical Model and Boundary Conditions

3.1 Numerical Models

Three-dimensional finite element analyses are performed using the commercial FEM software MIDAS-GTS (2005), which is a finite element analysis program for solving various geotechnical problems using 3-D continuum modeling. Two models (i.e., micro-scale and macro-scale) were considered to simulate the blasting process locally and globally. Compared to the conventional line-drilling method, the micro-scale model study puts emphasis on examining the vibration reduction efficiency of the precutting free surface method, while the macro-scale model is used to investigate the depth effect of the precutting free surface on vibration reduction.

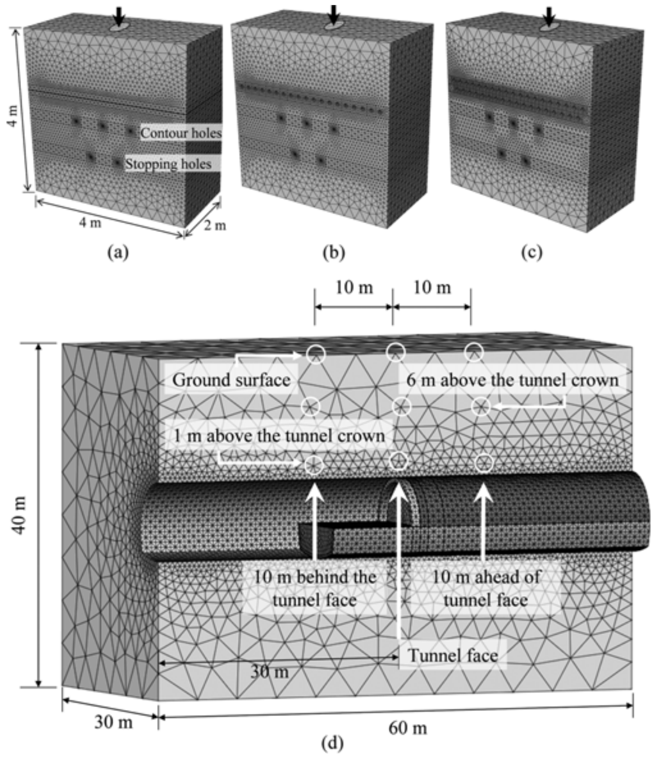

Fig. 3. Three-dimensional Finite Element Model Mesh: (a) Micro-scale Model with/without Precutting Free Surface of 5 cm (Case A and B), (b) Micro-scale Model with a Single Layer of Line-drilling (Case C), (c) Micro-scale Model with Double Layers of Line-drilling (Case D), (d) Macro-scale Model (Case E, F, G and H). Note: the Black Arrows at the Top of the Micro Model Indicate the Measuring Position of Vibration (Case A, B, C and D); the Depth of Precutting and Line-drilling is 1 m for All Micro-scale Models. White Circles in the Macro-scale Model Indicate the Interesting Nodes, which Have Been Monitored

The micro-scale model simulates stopping holes and contour holes around a tunnel excavation line, as shown in Fig. 3(a), 3(b) and 3(c). For all micro-scale model cases, blasting pressure is activated at the stopping holes and contour holes concurrently. Two cases (A and B) are investigated using the micro-scale model shown in Fig. 3(a): Case A simulates a conventional condition (i.e., barrier is absent) for the tunnel blasting process while Case B considers a continuous precutting free surface (10 cm thick and 1 m deep). Case C and Case D simulate a single layer of line-drilling (Fig. 3c) and double layers of line-drilling (Fig. 3d), respectively. The precutting free surface and line-drilling are located at 0.5 m above the center of the contour holes. Line-drilling has holes 90 mm in diameter and 1 m deep with a horizontal spacing of 200 mm while the vertical spacing between two drill holes is 200 mm; holes are arranged in parallel and in zig-zag manner for Case D. These four cases for micro-scale analyses are summarized in Table 1. Blasting-induced vibrations are measured at 2 m above the contour hole (i.e., the arrows in Fig. 3a, b and c) in order to evaluate the effect of the

Table 1. Cases for Numerical Analyses

Case		Descriptions		
		Barrier	Specification	Depth
Micro-scale	Case A	None (conventional)	N/A	0 m
	Case B	Precutting free surface	10 cm in thickness	1 m
	Case C	Single layer of line-drilling	Holes of 90 mm in diameter Horizontal spacing of 200 mm	1 m
	Case D	Double layers of line-drilling	Holes of 90 mm in diameter Horizontal and vertical spacing of 200 mm	1 m
Macro-scale	Case E	None (conventional)	N/A	0 m
	Case F-1	Precutting free surface	5 cm in thickness	1 m
	Case F-2	Precutting free surface	5 cm in thickness	2 m
	Case F-4	Precutting free surface	5 cm in thickness	4 m
	Case G-1	Precutting free surface	10 cm in thickness	1 m
	Case G-2	Precutting free surface	10 cm in thickness	2 m
	Case G-4	Precutting free surface	10 cm in thickness	4 m

precutting free surface.

The macro-scale model simulates a global tunnel section, which is a dual track subway section of Seoul metro line number 9. The width and height of the tunnel are 10.8 m and 9.2 m, respectively. The upper half section of 5.5 m in radius advances with a drill and blasting technique and is followed by a bench of 10 m, as shown in Fig. 3(d). Using the macro-scale model (Fig. 3d), seven cases are investigated in order to estimate the blasting-induced vibration with respect to the depth of the precutting free surface: Case E is without precutting free surface (i.e., conventional excavation), while the thickness of the precutting free surface is 5 cm for Case F (three cases) and 10 cm for Case G (three cases). The depth of the precutting free surface is various, with values of 1 m, 2 m, and 4 m in Case F and Case G. These seven cases for macro-scale analyses are summarized in Table 1 as well.

3.2 Ground Properties

Blasting practice often takes place in areas of relatively hard rock. Thus, this feasibility study adopts a hard rock, of which the properties are summarized in Table 2, for numerical analyses and considers the ground to be an elasto-plastic material, following the Mohr-Coulomb yield criterion. In small strain level, it has been reported that damping ratio is 6% in sand and 4~7% in clay (Howie and Amini, 2005). Damping ratio of rock mass also can be obtained from in-situ test or lab-test (Song *et al*., 2010). However, it is suggested by UBC-97 (International conference of building officials, 1997) to use 5% of damping ratio for dynamic analysis in general. Thus, damping ratio of rock mass for dynamic analysis is assumed to be 5% in this study.

A transmitting boundary (Lysmer and Wass, 1972) is applied to the micro- and macro-scale models in order to simulate a non-reflecting infinite ground condition. Eigenvalue analysis is initially performed to identify the periods of the first and second dominant frequency modes, at which a high portion of mass takes part in the vibration mode. The resulting periods are summarized in Table 3 for all cases.

Table 2. Rock Properties used for Numerical Analyses

Properties	Values
Density (g/cm^3)	2.6
Young's modulus (GPa)	25
Poisson's ratio	0.23
Cohesion (MPa)	3
Friction angle (°)	40
Earth pressure coefficient (K_0)	1.5

3.3 Blasting Pressure

Gurit of 17 mm in diameter, which is generally used for precise blasting, is applied to the contour holes. The charging condition of the contour holes is a decoupling charge with a decoupling index of 0.38 (i.e., diameter ratio of explosive to blasting hole = 17 mm/45 mm). For the stopping holes, an emulsion of 32 mm in diameter is considered to be fully charged. The properties of the explosives used for numerical analyses are summarized in Table 4 (Lee *et al.*, 2003).

Detonation pressure (P_D) can be calculated based on the equation suggested by the National Highway Institute (Konya and Walter, 1991):

$$P_D = \left(\frac{4.18\times10^{-7}\times SG\times(3.281104V)^2}{1+0.8SG}\right)\cdot 10^2 \quad (1)$$

Table 3. Periods of the First and Second Dominant Frequency Modes

Cases	Case A and B	Case C	Case D	Case E, F and G
1st Dominant period (sec)	0.010766	0.010939	0.010869	0.1232
2nd Dominant period (sec)	0.008118	0.008137	0.008075	0.1023

Table 4. Properties of Explosives

Properties	Emulsion	Gurit
Density (g/cm^3)	1.2	1.0
Detonation velocity (m/s)	5000	4000
Diameter (mm)	32	17

where SG is the specific gravity of the explosive (i.e., the density ratio of the explosive to water), V is the detonation velocity (m/s), and P_D is the detonation pressure (kPa). The maximum decoupled detonation pressure (P_B), considering the decoupling effect, can be calculated from the detonation pressure, as follows (Konya and Walter, 1991):

$$P_B = \left(\frac{de}{dh}\right)^3 \cdot P_D \quad (2)$$

where de is the diameter of the explosive and dh is the diameter of the drilled blasting hole.

Based on the properties given in Table 4, the maximum detonation pressure is estimated to be 210 MPa for contour holes and 6,800 MPa for stopping holes in the fully charged condition. The dynamic detonation pressure P acting on the blasting holes can be expressed as a transient time history function (Starfield and Pugliese, 1968; Histake *et al.*, 1983):

$$P(t) = 4P_B\left[\exp\left(\frac{-16338 \cdot t}{\sqrt{2}}\right) - \exp(-\sqrt{2} \cdot 1.338 \cdot t)\right] \quad (3)$$

where t is the elapsed time. Fig. 4 shows the transient time history of detonation pressures applied to the stopping holes and contour holes. To get a clear response, the detonation pressure is activated after 0.1 sec for the micro-scale model; it is activated at the beginning of the simulation (i.e., 0 sec) for the macro-scale model.

3.4 Boundary Conditions

For simplicity, the delay time of the blasting process is not considered and thus the stopping holes and contour holes are detonated at the same time. A realistic blasting process is simulated in the micro-scale models. The blasting pressure of the transient time history is assigned as a boundary condition for the dynamic numerical simulation and is applied normal to the internal surface of the bored blasting holes (i.e., stopping holes and contour holes).

In real blasting practice, depending on the purpose, many blasting holes are drilled, charged and detonated using an electric delay detonator to precisely control the delay time. However, in the case of macro-scale models, not every bored blasting hole at the tunnel face can be simulated precisely and delayed detonation is difficult to simulate because the size of the elements for drilled blasting holes should be on the millimeter scale, while the total scale of the macro model is 60 m. Simplification cannot be avoided and the detailed simulation of drilled blasting holes is inefficient for the purpose of a feasibility study. Thus, it is assumed that the detonation pressure is one single pulse that is concentrated in the stopping holes, is normal to the excavation surface, and acts on a location 0.5 m from the excavation line. Especially, to obtain the blasting-induced vibration ahead and behind the tunnel face, as well as at the tunnel face, the blasting simulation is conducted in the upper tunnel face, which has an advance length of 30 m and a bench excavation of 10 m, as shown in Fig. 3(d).

4. Numerical Results and Discussion

4.1 Micro-scale Analysis – Comparison

The significance of the precutting free surface-aided tunnel blasting method is observed through the micro-scale simulation with idealized blasting pressure. When blasting is carried out, the contour plots of the maximum vertical displacement and peak particle velocity in the vertical direction are shown in Fig. 5 and Fig. 6, respectively. The upper ground above the excavation line suffers significant vibration in Case A, in which the precutting free surface is absent (Fig. 5a and Fig. 6a). However, it can be clearly observed in the Case B that the precutting free surface acts as a complete seismic barrier, so that the separated upper ground is less affected by the blasting pressure (Fig. 5b and Fig. 6b).

The blasting wave propagation characteristics through the single layer and double layers of line-drilling are shown in Fig.

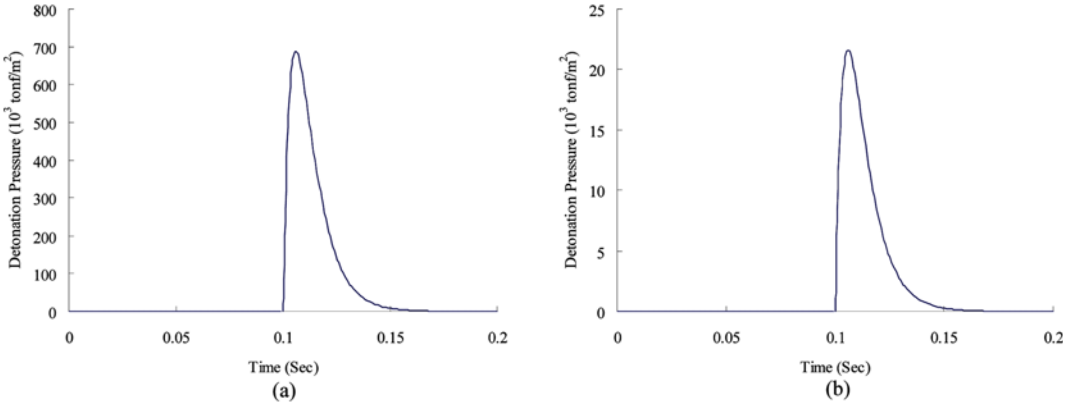

Fig. 4. Time History Functions for Detonation Pressure in Micro-scale Model: (a) Stopping Holes, (b) Contour Holes

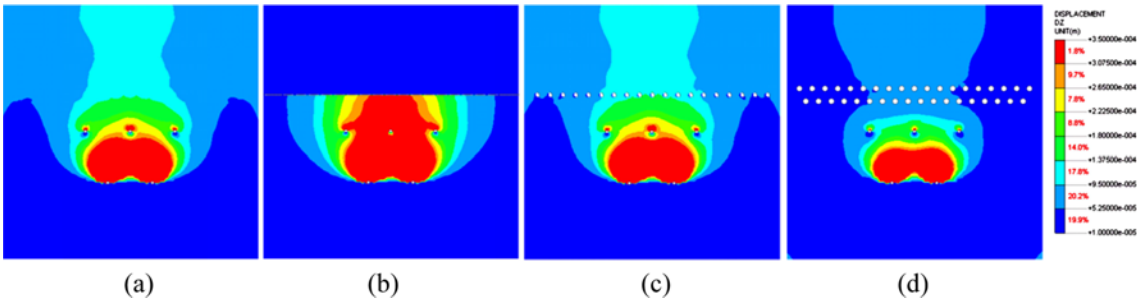

Fig. 5. Maximum Vertical Displacement Contour: (a) Case A, (b) Case B, (c) Case C, (d) Case D

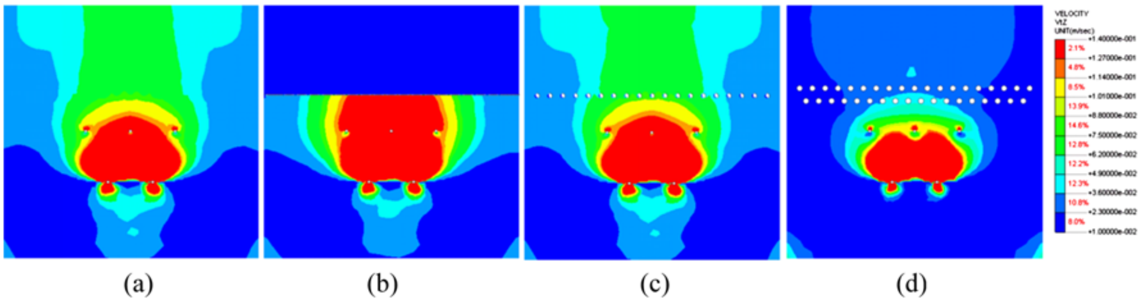

Fig. 6. Peak Particle Velocity in the Vertical Direction: (a) Case A, (b) Case B, (c) Case C, (d) Case D

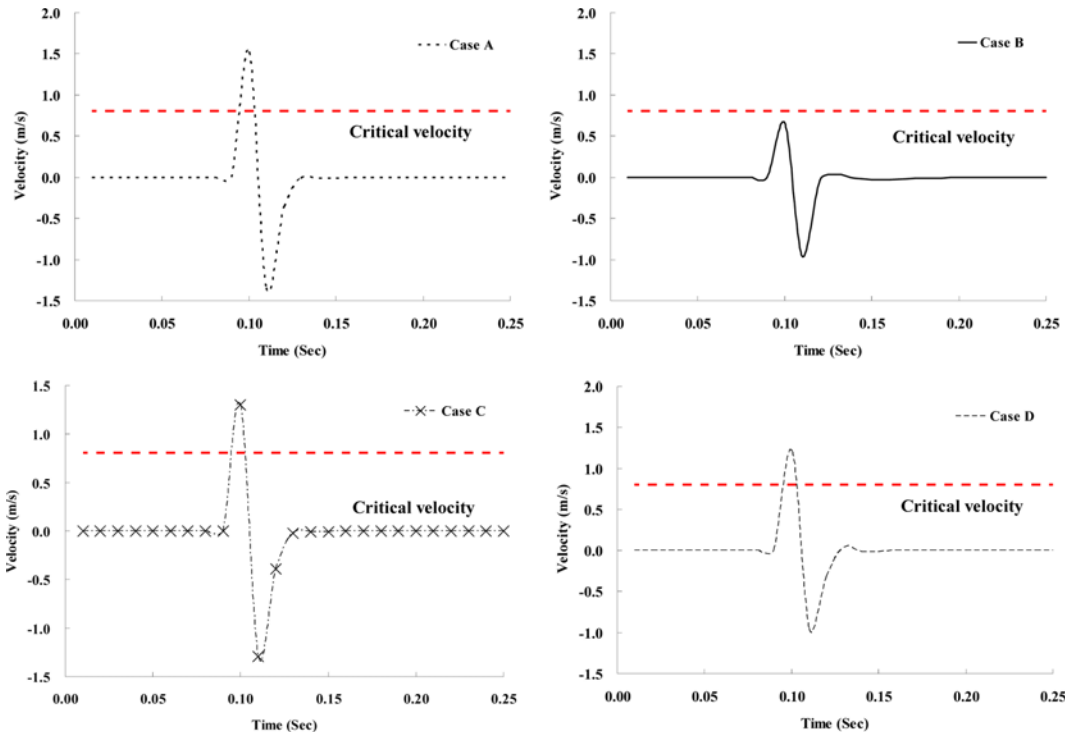

Fig. 7. History of Vertical Particle Velocities Measured at 2 m Above the Contour Hole (at the Top of the Micro-scale Model in Fig. 3a, 3b, and 3c)

5(c, d) for maximum vertical displacement and in Fig. 6(c, d) for peak particle velocity. Displacement and particle velocity contour plots for the single layer of line-drilling (Fig. 5c and 6c) are not much different from those in the results obtained from Case A, which did not have a seismic barrier (Fig. 5a and 6a). This is because the seismic wave induced by tunnel blasting can still propagate through regions connecting the tunnel section and the ground around the tunnel, even after the installation of line-drilling along the excavation line. Although maximum vertical displacement and peak particle velocity decrease as the number of line-drilling layers increases, the neighboring ground where the double layers of line-drilling are applied still experiences significant blasting-induced seismic waves (Fig. 5d and 6d).

Most rock masses suffer from damage due to blasting-induced vibration when the peak particle velocity is higher than 700 mm/s (Holmberg and Persson, 1979; Rustan, 1985; Dey, 2004). Thus, a critical peak particle velocity is assumed to be 700 mm/s. Fig. 7 presents the time history of the peak particle velocity obtained 2 m above the contour holes (the micro scale model in Fig. 3). Except the result for Case B (with a precutting free surface), peak velocities in the other cases (Cases B, C and D) exceed 700 mm/s. This implies that the 2 m deep neighboring ground takes blasting-induced damage, even after the double layers of line-drilling are applied. However, the precutting free surface prevents the propagation of the blasting-induced seismic wave and renders a significant reduction of the peak particle velocity, making it less than 650 mm/s.

In order to quantify the effect of precutting free surfaces on blasting-induced vibration, the reduction rate is defined as follows:

$$R_\gamma = \left[\frac{PPV_g - PPV_{barrier}}{PPV_g}\right] \times 100(\%) \tag{4}$$

where R_r is the reduction rate of the peak particle velocity induced by a barrier, PPV_g is the peak particle velocity for general cases without barriers, and $PPV_{barrier}$ is the peak particle velocity for those cases with barriers. The reduction rate of Case C (a single layer of line-drilling) is R_r = 13.8%, which is very similar to the result (R_r = 13.4%) obtained by Park *et al.* (2009). The reduction rate of Case D (double layers of line-drilling) is R_r = 20.4%, which is little higher than the result (R_r = 19%) obtained from 2D analysis by Park *et al.* (2009). In Case C and Case D, the value for R_r obtained in this study is a little higher than that obtained by Park *et al.* (2009) because the diameter of the drilling holes used in this study was 90 mm, which is larger than that used in the previous study (45 mm). Even though the detailed geometry and specifications are not exactly identical to those of the previous study, however, the three dimensional numerical simulation carried out in this study is in good agreement with that of the previous study and is valid for further analysis. When the precutting free surface is applied (Case B), the reduction rate becomes ~57%, suggesting that the precutting free surface reduces blasting-induced vibration significantly.

Therefore, contour holes can be replaced with a precutting free surface in order to effectively reduce blasting-induced vibration. It is also expected that the construction cost and installation time will decrease due to a decrease in the number of drilling holes, the weight of explosive charges, the overbreak space, and the excavation-damaged zone. In particular, the reductions of the overbreak space and the excavation-damaged zone also enhance the safety of tunnel construction.

4.2 Macro-scale Analysis – Length Effect

When there is no seismic barrier, the time history of the vertical displacements measured above the tunnel face is as shown in Fig. 8. The blasting-induced vibration decreases as the distance

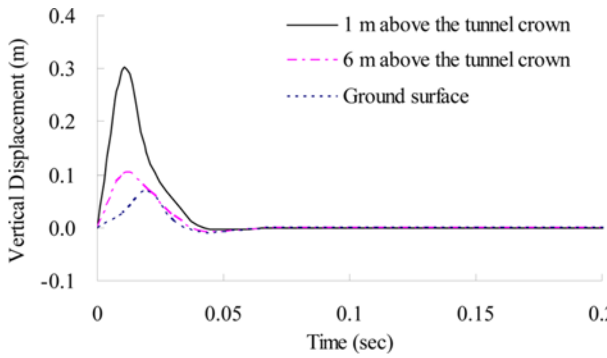

Fig. 8. History of Vertical Displacements Measured Above the Tunnel Face when There is no Precutting Free Surface

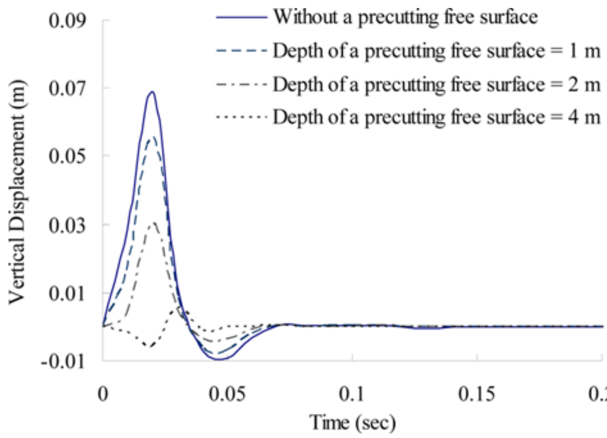

Fig. 9. Time History of Vertical Displacements Measured at the Ground Surface Above the Tunnel Face with Respect to the Depth of Precutting Free Surface

from the blasting source increases. In such a case, the decay of blasting-induced vibration is governed mainly by material damping and geometric spreading. Also, the peak of the blasting wave is delayed as the distance from the tunnel crown to the monitoring position increases. The peak of the time history plot measured at the ground surface, shown in Fig. 8, is used as a reference for cases considering the precutting free surface; the maximum vertical displacement is estimated to be 0.07 m, which is used as a reference value.

Figure 9 shows the time history of vertical displacements measured at the ground surface above the tunnel face depending on the depth of the precutting free surface (i.e., 1 m, 2 m, 4 m). These results are obtained from the macro-scale model case with a precutting free surface 5 cm in thickness (i.e., Case E, Case F-1, Case F-2, and Case F-4). The maximum vertical displacement decreases as the depth of the precutting free surface increases. When the depth of the precutting free surface is 4 m, the reduction rate of displacement is estimated to be 90%. In summary, most of the blasting-induced vibration can be significantly reduced with the aid of a precutting free surface.

Figure 10 presents the maximum vertical particle velocity measured at different horizontal locations with respect to the depth of the precutting free surface. As the depth of the

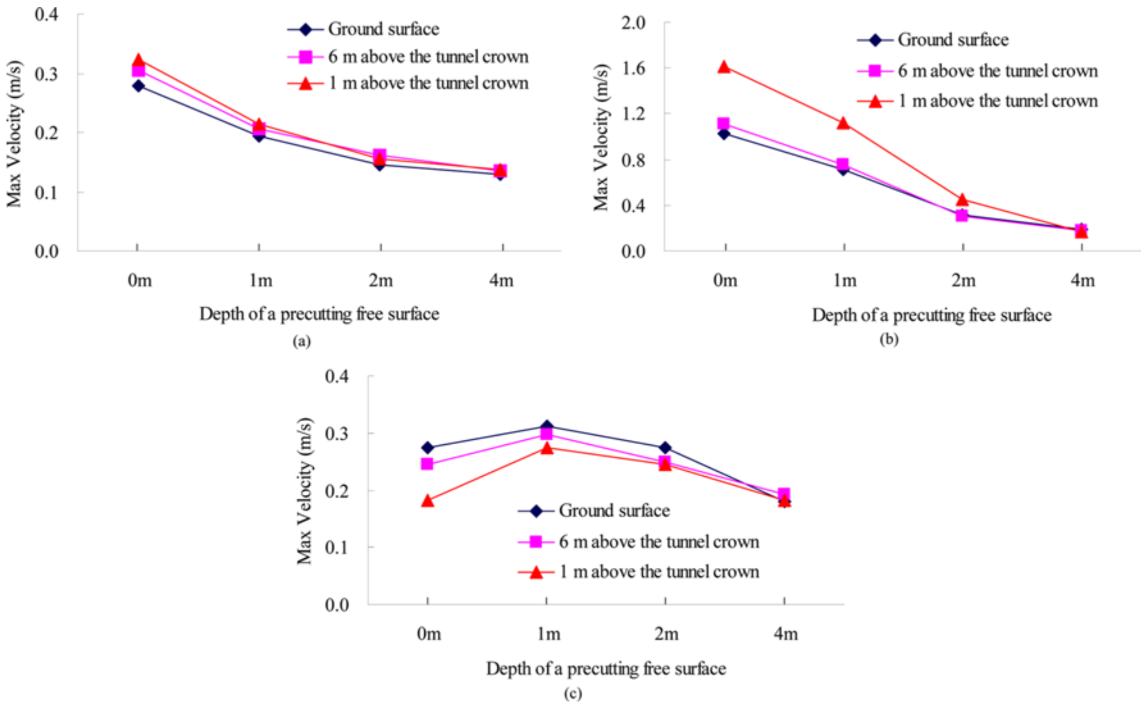

Fig. 10. Maximum Vertical Particle Velocities Depending on the Depth of Precutting Free Surface: (a) At 10 m Behind the Tunnel Face, (b) At the Tunnel Face, (c) At 10 m Ahead of the Tunnel Face

precutting free surface increases, the blasting-induced vibration decreases at the tunnel face and behind the tunnel face (Fig. 10a and 10b). The reduction rate and its trend behind the tunnel face are similar to those of the ground surface and the tunnel crown (Fig. 10a). As the depth of the precutting free surface increases, the reduction of vibration is most significant at 1 m from the tunnel crown above the tunnel face (Fig. 10b). This implies that the depth of the excavation-damaged zone and loosening earth pressure, which can act on the tunnel structure, can be significantly reduced with a precutting free surface. Also, blasting-induced vibration transmitted to the ground surface above and behind the tunnel face can be significantly reduced, so that the blasting effect on tunnel supports (such as shotcrete) and structures on the ground surface can be minimized. Guided blasting waves cause wave concentration and induce a slight increase of vibration ahead of the tunnel face. However, as the depth of the precutting free surface increases, the vibration ahead of the tunnel face can be reduced as well.

The numerical results can be also interpreted in view of the vertical distance from the blasting source. The blasting-induced vibration measured above the tunnel face is the largest compared to those measured ahead or behind the tunnel face. As the depth of the precutting free surface increases, blasting-induced vibrations measured behind the tunnel face and above the tunnel face decrease for all positions. On the other hand, as the depth of the precutting free surface increases, the blasting-induced vibration measured ahead of the tunnel face increases and becomes larger than that measured at the tunnel face and behind the tunnel face when the depth of the precutting free surface is 4 m.

When the depth of the precutting free surface is 1 m, the blasting-induced vibration measured ahead of the tunnel face is slightly larger than that of the case without a precutting free surface. The blasting wave is guided by the precutting free surface and propagates more ahead of the tunnel face because seismic waves cannot be transmitted to the ground surface and can be entrapped in the blasting face. However, the blasting-induced vibration ahead of the tunnel face can also be reduced with a precutting free surface of 4 m in depth.

Numerical results obtained from the 10 cm thick precutting free surface (Case G-1, -2, -4) are identical to those from the 5 cm thick precutting free surface (Case F-1, -2, 4), suggesting that the vibration reduction rate is not affected by the thickness of the precutting free surface but is governed by the presence of a precutting free surface. The reduction rate of blasting-induced vibration is closely related to the depth of the precutting free surface. Thus, a thin and deep precutting free surface may be recommended for the effective reduction of blasting induced-vibration and a cost-effective tunneling process. However, an excavation-induced deformation may occur in the precutting free surface zone, which defect could waterjet cutting work. The thickness of the precutting free surface is site-dependent and should be determined based on an in-situ observation of the excavation-induced deformation.

Figure 11 presents the combination of displacement components in the XYZ direction induced by the detonation pressure applied at 0.5 m from the excavation line. As the depth of the precutting free surface increases, the displacement contour ahead of the tunnel face transforms itself from the horizontal direction to the

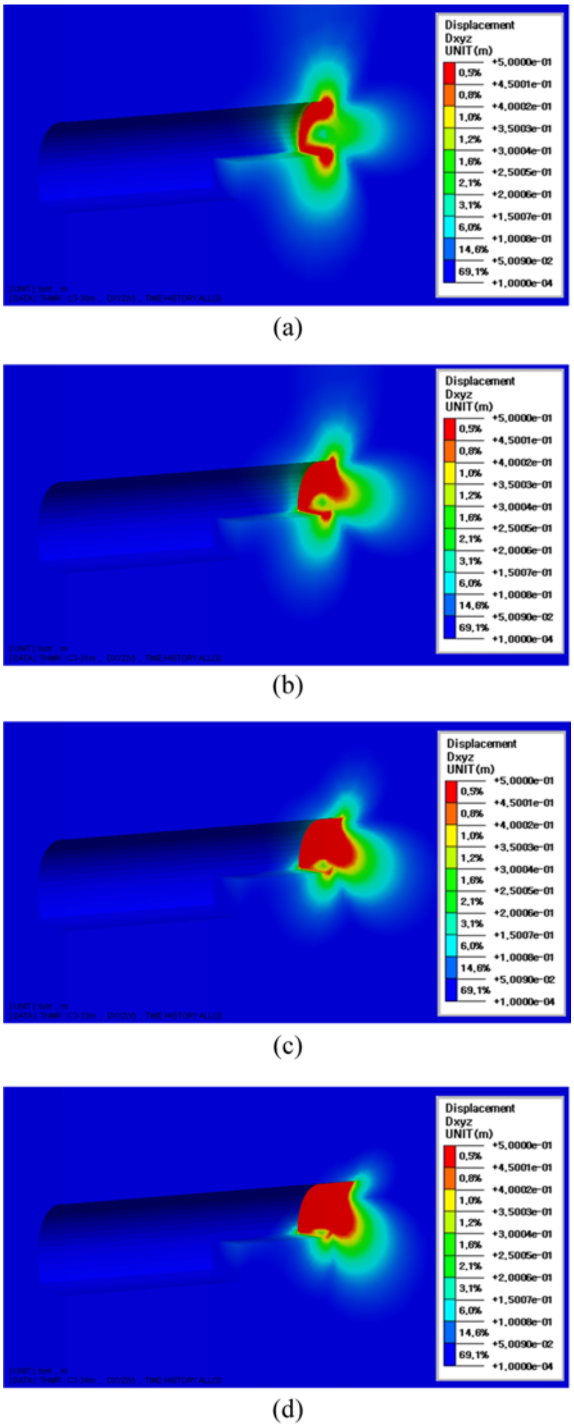

Fig. 11. XYZ-displacement: (a) Depth of Precutting Free Surface is 0 m, (b) Depth of Precutting Free Surface is 1 m, (c) Depth of Precutting Free Surface is 2 m, (d) Depth of Precutting Free Surface is 4 m.

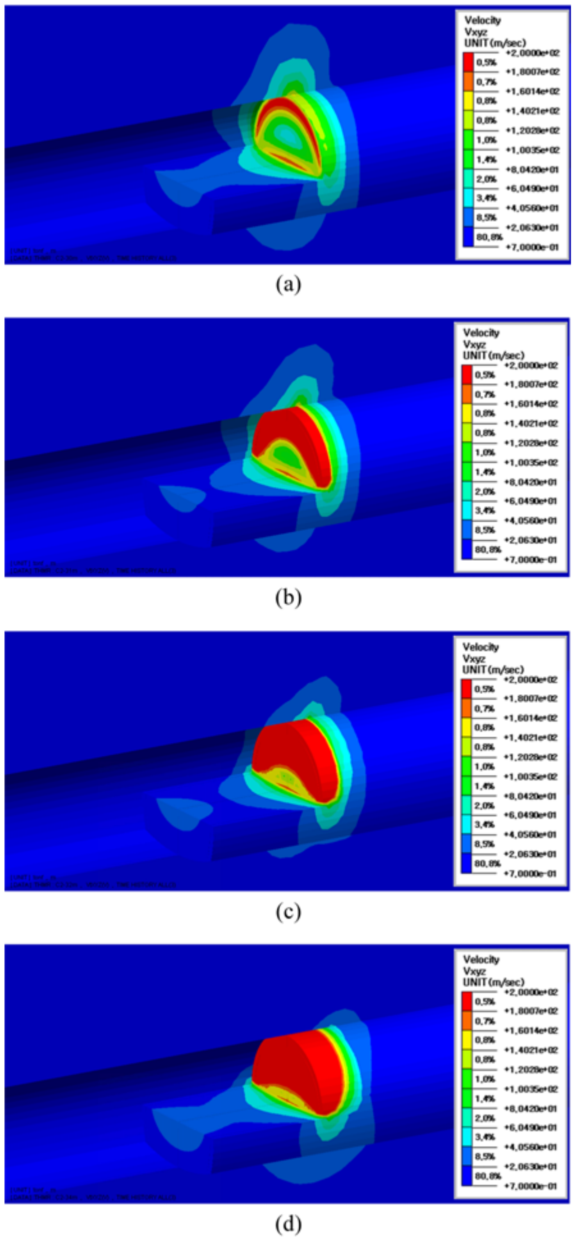

Fig. 12. Three Dimensional Contour of Peak Particle Velocity in XYZ Direction (Above 700 mm/sec): (a) Depth of Precutting Free Surface is 0 m, (b) Depth of Precutting Free Surface is 1 m, (c) Depth of Precutting Free Surface is 2 m, (d) Depth of Precutting Free Surface is 4 m.

vertical and the length of the contour plot in the vertical direction decreases. It can be seen that the blasting energy remaining in the interior region concentrates at the target face and that the detonation pressure hardly affects the neighboring ground around the tunnel. Thus, a blasting-induced damaged zone can be significantly reduced via the installation of a precutting free surface along the tunnel perimeter. This result gives us the insight that the vibration energy induced by blasting cannot be propagated through the free surface and entrapped inside the target face. In such a case, the entrapped wave tends to resonate at the target surface, so that the fragmentation efficiency can be increased. In this way, it is possible to break a stronger rock mass with a lower blasting pressure.

In particular, the potential blasting-damaged zone at which the peak particle velocity is greater than 700 mm/sec is presented in

Fig. 12. As the depth of the precutting free surface increases, the blasting-induced excavation-damaged zone significantly decreases in the vertical direction. The peak particle velocity concentrates at the tunnel face as the depth of the precutting free surface increases. This implies that the blasting efficiency can be maximized with the aid of a precutting free surface, ultimately resulting in a reduction of the loosening earth pressure acting on the tunnel structure (such as shotcrete and concrete lining).

5. Conclusions

In the study presented here, an innovative tunnel blasting system, which installs a continuous arch void (i.e., precutting free surface) along the tunnel perimeter, is proposed in order to minimize blasting-induced vibration. To examine the feasibility of the proposed tunnel blasting technique, we carried out three dimensional finite element-based numerical analyses. The salient findings obtained from the numerical study can be summarized as follows.

Through the micro-scale analyses, it was found that blasting-induced seismic waves can propagate through the regions connecting a tunnel section and the ground around the tunnel, even after the installation of line-drilling layers. Although the displacement and particle velocity decrease as the number of line-drilling layers increases, the neighboring ground is still affected by the blasting-induced seismic wave. However, a precutting free surface can effectively prevent the propagation of the blasting-induced seismic wave and reduce the peak particle velocity below a critical level.

From the macro-scale analyses, it was found that the vibration reduction rate is not affected by the thickness of the precutting free surface but depends only on the presence of a precutting free surface. The reduction characteristic of the blasting-induced vibration is closely related to the depth of the precutting free surface. As the depth of precutting free surface increases, the reduction rate of the blasting-induced vibration can be significantly increased and the excavation damaged zone can be minimized. This implies that the effect of blasting-induced vibration on the tunnel support (such as shotcrete) and structures on the ground surface can be significantly reduced with the installation of a precutting free surface around the tunnel perimeter. No vibration energy induced by blasting can transmit through the free surface. Then, guided and entrapped blasting waves tend to resonate at the target surface, so that the fragmentation efficiency can be increased. In conclusion, a thin and deeper precutting free surface is preferable for the effective reduction of blasting-induced vibration. The large amount of seismic energy induced by tunnel blasting can be effectively screened by a continuous seismic barrier created by precutting tools such as abrasive waterjets.

The proposed tunnel blasting system also has additional benefits: The construction cost will decrease due to a decrease in the number of drilling holes, the weight of explosive charges, the overbreak space, and the excavation-damaged zone. The loosening earth pressure acting on the tunnel structure (such as shotcrete and concrete lining) can be reduced; and in particular, the reduction of the overbreak space and excavation-damaged zone enhances the safety of tunnel construction. Due to these features, cost-effective tunneling can be achieved. For the practical application of the proposed method, a prototype of the precutting system will be developed shortly. Furthermore, laboratory tests and field tests will be conducted in the near future to verify the numerical analysis results presented in this study.

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