Thesis Summary

Reduction of Blast-Induced Vibration in Tunnelling
Using Barrier Holes and Air-deck

Presented by
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CONTENTS

ABSTRACT                        2

1. INTRODUCTION                  2

2. BASIC CONSIDERATIONS         4

   2.1 Screening of blast-induced waves for reducing ground vibration
      in the transverse direction of a tunnel  4

   2.2 Suppression of blast-induced waves for reducing ground vibration
      in the direction of tunnelling          6

3. PARAMETRIC NUMERICAL STUDY    8

   3.1 Numerical modeling using the non-linear hydrocode   8

       3.1.1 Basic procedure                       8

       3.1.2 Modeling the source of explosion       8

       3.1.3 Modeling the stemming material         9

       3.1.4 Modeling the ground                    9

   3.2 Assessment method for vibration-reduction effect 10

   3.3 Numerical investigations of the effectiveness of line-drilling method 11

       3.3.1 Effect of the spacing and diameter of drill holes  11

       3.3.2 Effect of the number of drill holes and their arrangement 12

       3.3.3 Effect of the distance between blasthole and line-drilling 13

       3.3.4 Quantitative information on the drilling of barrier holes 13

   3.4 Numerical investigations of the effectiveness of bottom-air-deck method 14

       3.4.1 Effect of the length of bottom-air-deck on the vibration reduction 14

       3.4.2 Effect of the length of bottom-air-deck on the excavation efficiency 17

4. FIELD EXPERIMENTAL STUDY      19

   4.1 Assessment method for vibration-reduction effect 19

   4.2 Field experiments of line-drilling method        19

       4.2.1 Single-hole experiment                  19

       4.2.2 Full-scale experiment                   21

   4.3 Field experiments of bottom-air-deck method       22

       4.3.1 Effect of the length of bottom-air-deck on the vibration reduction 22

       4.3.2 Effect of the length of bottom-air-deck on the excavation efficiency 25

5. DESIGN CONDITIONS FOR FIELD APPLICATION 26

   5.1 Design conditions of line-drilling method         26

   5.2 Design conditions of bottom-air-deck method       26

6. CONCLUSIONS AND DISCUSSION     28

REFERENCES                      29
ABSTRACT

In the present study, two kinds of vibration-reduction methods for tunnelling, which are applicable according to the location of a nearby structure, were proposed: line-drilling method; and an air-deck method. Numerical investigations were carried out for obtaining quantitative information on the effectiveness of both methods. The non-linear hydrocode which can numerically model chemical explosives was used for realistically simulating blasting problems. Field experiments were carried out at several sites in order to verify the numerical results on the effectiveness of both methods. The numerical and experimental results agreed well with each other. It was revealed that both methods effectively reduced blast-induced vibration according to the location of a structure. From a comparison between the numerical and experimental results, it was concluded that when both methods are applied to tunnelling sites, the vibration-reduction effects that were predicted through the numerical study can be expected. On the basis of the conclusion, design conditions of both methods for the reduction of blast-induced vibration were proposed by introducing the concept of factor of safety.

1. INTRODUCTION

Blast-induced vibration may cause damage to nearby structures and local inhabitants, and in the case of serious problems, entails huge time and cost overruns in construction. In order to solve the problem of blast-induced vibration, various methods have been examined based on the screening or suppression of blast-induced waves. However, most of the methods have not been quantitatively studied for their effect in reducing ground vibrations and have required special equipment or complicated working conditions. For these reasons, most of the methods have not been widely used. Meanwhile, for a tunnel that is being excavated in one direction, an effective method for the reduction of vibration in the direction of tunnelling is needed. However, up to now, there have not been many researches on the reduction of blast-induced vibration in the direction of tunnelling, which refers to the reduction of vibration in front of a vertical plane, including a tunnel face, as shown in Fig. 1.

The present study proposed line-drilling and an air-deck method for reducing blast-induced vibration in the transverse direction of a tunnel and in the direction of tunnelling, respectively. The reduction of vibration in the transverse direction of a tunnel refers to the reduction of vibration in rear of a vertical plane, including a tunnel face, as shown in Fig. 1. The air-deck method (hereafter referred as the “bottom-air-deck method”) involves the use of a thin paper-tube at the bottom of a blasthole. A quantitative assessment of the effectiveness of both methods was numerically and experimentally carried out. The parameters of line-drilling were spacing and diameter of drill holes, distance between the blasthole and line-drilling, and the number of rows of drill holes, including their arrangement, with the parameter of bottom-air-deck, being the length of the air-deck at the bottoms of blastholes (hereafter referred as “bottom-air-deck”). The effectiveness of both methods was assessed via a comparison of the amplitude of
the vibration or the advance between two cases, one with line-drilling (or bottom-air-deck) and the other without. The advance refers to the average length in the direction of tunnelling, which is excavated through tunnel blasting.

In the numerical investigations, the non-linear hydrocode, AUTODYN, which can numerically model explosives, was used for realistically simulating blasting problems. From the numerical investigations of line-drilling method, a correlation equation of vibration-reduction effect which gives quantitative information on the drilling of barrier holes was derived. From the numerical investigations of bottom-air-deck method, the ranges of vibration-reduction effects for various lengths of bottom-air-deck were obtained. The reduction in excavation efficiency occurred due to bottom-air-deck and the reduction in advance was approximately proportional to the length of bottom-air-deck. Bottom-air-deck method was also found to be more effective than the conventional method of reducing the advance per round under certain design conditions.

In order to verify the numerical results, field experiments were carried out. The results of numerical analyses were compared with those of the field experiments. Single-hole and full-scale field experiments were carried out at several sites: quarry; mine; and tunnel sites. Good agreement was found from a comparison between the numerical and experimental results. From the comparison, it was concluded that when both methods are applied to tunnelling sites, the vibration-reduction effects that were predicted through the numerical study can be expected. On the basis of the conclusion, design conditions for obtaining vibration-reduction effects of 10-20% and 10-25% in the transverse direction of a tunnel and in the direction of tunnelling, respectively, were proposed by introducing the concept of ‘factor of safety’ for the results that were predicted through the numerical investigations.

Fig. 1 Directions of the reduction of blast-induced vibration in tunnelling.
2. BASIC CONSIDERATIONS

2.1 Screening of blast-induced waves for reducing ground vibration in the transverse direction of a tunnel

It has become well known that the use of a trench as a screening method of waves reduces the amplitude of ground vibration as well as the high frequency components. Fig. 2 shows a schematic of the trench effect on vibration propagation, which shows that the amplitude of high frequency components of ground motion generated by a vibration source are reduced by a trench. This means that a trench absorbs vibrational energy related to high frequency. $E_1$, $E_2$, and $E_{total}$ indicated in Fig. 2 are the energies relating to vibration propagation.

When studying the screening of elastic waves, it is convenient to subdivide the problem into two categories: (1) active isolation (isolation at the source); and (2) passive isolation (screening at a distance) (Woods, 1968). With active isolation, a barrier is located at points close to or surrounding the source of vibration to reduce the amount of wave energy (Fig. 3). Conversely, with passive isolation, a barrier is located at points remote from the source of vibration, but near a site where the amplitude of vibration must be reduced (Fig. 4).

When blasting is carried out in the vicinity of a structure or in urban areas, the blast-induced ground vibration can cause claims from the neighbors or structural damage where the amplitude of vibration is greater than an acceptance limit. As mentioned earlier, passive isolation is applied at points near a site for the necessary vibration reduction. Since passive isolation is constructed in the vicinity of a structure, the construction work can give rise to additional noise and vibration prior to the primary construction operations. The noise and vibration can also cause secondary pollution from both environmental and structural views. Therefore, in the screening of waves related to blasting, active isolation is believed to be more effective than passive isolation. In addition, when passive isolation is installed in the vicinity of a structure during blasting work, it is necessary for the original ground state to be restored following completion of construction, as the isolation will no longer be required. In conclusion, it is believed that compared to active isolation, passive isolation is not practically effective in the screening of blast induced waves from various constructional features. Therefore, only the problem of active isolation was investigated in the present study.

There are three screening methods for reducing blast-induced vibrations in the transverse direction of a tunnel: (1) a barrier wall; (2) pre-splitting; and (3) barrier holes. A barrier wall, i.e., a trench is the most effective screening method, in that it is capable of relatively complete isolation, but does requires great expense. In addition, the excavation of a barrier wall at tunnelling sites is not practical from a constructional point of view. Pre-splitting can reduce the amount of drilling compared to the other methods, but in the case that the amount of explosive for pre-split blasting is not accurate, cracks for screening blast-induced vibration cannot be generated or the amplitude of vibration induced by pre-splitting can be greater than that induced by primary blasting. Barrier holes, i.e., line-drilling can eliminate the problems of pre-splitting, because line-drilled holes are not loaded and can reduce the
amount of drilling compared to a trench. In addition, if there is quantitative information on the drilling of barrier holes, line-drilling is the most practical method compared to the other methods. Therefore, the present study proposed line-drilling method for reducing blast-induced vibrations in the transverse direction of a tunnel.

Fig. 2 Schematic of the trench effect on vibration propagation

Fig. 3 Schematic of active isolation for the reduction of ground vibration

Fig. 4 Schematic of passive isolation for the reduction of ground vibration
2.2 Suppression of blast-induced waves for reducing ground vibration in the direction of tunnelling

The amplitude of blast-induced vibration, i.e., the particle velocity, is influenced by the type of explosive, charge weight per delay, distance from the blasting source to the point of monitoring, ground (rock mass) condition, etc. The particle velocity can be expressed as follows:

\[ V = K \left( \frac{D}{W^b} \right)^n \]

where \( V \) is the particle velocity, \( K \) is a constant that depends upon the ground condition as well as the conditions of blasting, \( D \) is the distance from the blasting source to the point of monitoring, \( W \) is the charge weight per delay, and \( b \) and \( n \) are constants that depend upon the ground condition.

In the above equation, the distance, \( D \), from the blasting source and the constants, \( b \) and \( n \), are uncontrollable parameters unless the blasting site is changed, while the constant, \( K \), and the charge weight per delay, \( W \), are controllable parameters that may be changed according to the conditions of blasting. In relation to the controllable parameters, there are several conventional methods for suppressing blast-induced vibration in the direction of tunnelling: reduction of the charge weight per delay by using the delay detonator or by reducing the length of advance per round; creation of a new internal free face through a hole of large bore in the cut area; a deck-charge using a spacer or stemming material; and use of low-velocity explosives. The reduction of the charge weight per delay, especially through the reduction in the advance per round, necessarily causes time and cost overruns in construction. Further, special equipment, such as a large-bore drilling machine, is needed for creating a new internal free face in the cut area. Therefore, these methods are neither practical nor cost-effective from a constructional point of view.

A deck-charge whereby explosives are separated from other explosives by inert material or air cushions in the same blasthole can significantly reduce the charge weight per delay. However, since a deck-charge requires two or more detonators in the same blasthole, it is difficult to load blastholes and a detonator with an accurate firing time, such as an electronic detonator, is needed. In addition, due to the separation of explosives in the same blasthole, dead pressing, i.e., the desensitization of an explosive that is caused by pressurization, is most likely to occur. Therefore, a deck-charge is not usually suitable for reducing blast-induced vibration in the direction of tunnelling. Finally, since low-velocity explosives have a low rate of reaction and thus low pressures, the low-velocity explosives are more suitable for quarrying rather than tunneling.

As mentioned above, since the conventional methods to reduce blast-induced vibration in the direction of tunneling are not quite effective, they are not widely used. In the present study, a bottom-air-deck method was newly investigated. As early as 1940, Mel’nikov (1940) noted the efficiency of using a charge with air gaps to obtain good fragmentation. Melnikov & Marchenko (1971), Mel’nikov et al. (1979), Marchenko (1982), and Fourney et al. (2006) theoretically and experimentally studied the principle of air-decks. Mead et al. (1993) and Moxon et al. (1993) investigated the improvement of the fragmentation of air-decks. Jhanwar et al. (1999) and Jhanwar & Jethwa (2000) carried out experiments in
an open pit mine for examining the improvement of the fragmentation and the vibration reduction of an air-deck, which was placed in the middle of an explosive column. However, prior research, including Jhanwar et al. (1999) and Jhanwar & Jethwa (2000), did not investigate the vibration-reduction effect of air-decks from the perspective of reducing blast-induced vibration in the direction of tunnelling.

According to Marchenko (1982), when a charge is blasted with air gaps, the products of explosion can no longer generate a powerful shock wave in the medium because they can expand into the air gap after the charge detonates, as a result of which their pressure decreases. On the basis of such a principle, the present study has assumed that an air-deck at the bottom of a blasthole, i.e., a bottom-air-deck, can suppress blast-induced vibration in the direction of tunnelling. The essence of this idea is that by installing an air-deck at the bottom of a blasthole, the initial pressure of the products of explosion, which is transmitted to the surrounding ground through the bottoms of blastholes, decreases. Further, the distance from the blasting source to the point of monitoring increases and thus, one can reduce blast-induced vibration in the direction of tunnelling.

The present study has used a thin paper-tube for bottom-air-deck, as shown in Fig. 5. The figure shows the charge pattern of the bottom-air-deck method proposed in the present study and the paper-tube for bottom-air-deck, of which the inner diameter and thickness were 31.8 mm and 1.1 mm, respectively.

![Fig. 5](image)

Fig. 5 (a) Charge pattern of the bottom-air-deck method proposed in the present study, and (b) paper-tube used for bottom-air-deck.
3. PARAMETRIC NUMERICAL STUDY

3.1 Numerical modeling using the non-linear hydrocode

Since a hydrocode is suited for simulating a high-velocity impact, especially an explosion, the present study used the non-linear hydrocode, AUTODYN, which incorporates finite-element analysis, computational fluid dynamics, a mesh-free or meshless (smoothed particle hydrodynamics, SPH) capability, and coupling between these techniques and material physics.

3.1.1 Basic procedure

The severe distortion of Lagrange grids in the finite element method (FEM) gives rise to errors as well as minuscule time-steps. Hundreds to thousands of iterations can be performed for equilibrating the density, pressure, and internal energy in regions of calculation that are of no interest and that have little effect on the final result. On the other hand, SPH, which is a mesh-free Lagrangian technique that was originally developed by Lucy (1977) and Gingold & Monaghan (1977), has the advantage of computing a large deformation problem, owing to the absence of a real mesh. In consideration of the above characteristics of both Lagrangian FEM and SPH, the present study used SPH for modeling the materials in large-deformation regions and modeled low-deformation materials using elements of Lagrangian FEM.

3.1.2 Modeling the source of explosion

The JWL (Jones-Wilkins-Lee) equation of state (EOS), which is more common than other EOSs, especially in hydrodynamic calculations (Lan et al., 1993), was used in the present numerical study and TNT (trinitrotoluene), which has been widely applied in blasting problems, was used as a source of explosion. The JWL EOS and parameters for the TNT (Lee et al., 1973) are as follows:

\[
P = A \left(1 - \frac{\omega}{R_1 V}\right) \exp^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right) \exp^{-R_2 V} + \frac{A e}{V}
\]

where \(V\) is the specific volume, \(e = 6.000 \times 10^6 \text{ kJ/m}^3\) is the specific internal energy, and \(A = 3.738 \times 10^5 \text{ MPa}\), \(B = 3.747 \text{ MPa}\), \(R_1 = 4.15\), \(R_2 = 0.9\), and \(\omega = 0.35\) are the TNT constants that are determined from the cylindrical expansion test.

It is common to use dynamite-type or emulsion-type explosives for excavating ground. Therefore, the following empirical equation of the relative weight strength (RWS) of explosives (Jimeno et al., 1995) was used to convert the amount of the dynamite-type or emulsion-type explosive to that of the TNT:

\[
RWS = \left(\frac{\rho_e \times VOD_e^2}{\rho_o \times VOD_o^2}\right)^{1/3}
\]

where \(\rho_e\) is the density of the explosive (g/cm\(^3\)), \(VOD\) is the velocity of detonation (m/s), and \(\rho_o\) and \(VOD_o\) refer to the corresponding values for the standard explosive.
3.1.3 Modeling the stemming material

It is necessary to model the stemming material in order to realistically simulate tunnel blasting. Non-cohesive sand of loose compactness is commonly used as the stemming material in tunnel blasting. Therefore, the present study used the mechanical properties of non-cohesive and loose sand that are generally used (Dunham, 1954; Hunt, 1984). The properties of the loose sand were determined for round and uniformly graded sand particles. The N-value of the loose sand, which was obtained from the standard penetration test, was assumed to be 4-10 (Dunham, 1954; Hunt, 1984). Accordingly, the density, bulk and shear modulus, and angle of internal friction of the loose sand were 1,800 kg/m³, 33.3 MPa, 11.1 MPa, and 25°, respectively.

3.1.4 Modeling the ground

In the present study, the RHT (Riedel, Hiermaier, and Thoma) model, which was originally developed for modeling the behavior of concrete under dynamic loading (Riedel et al., 1999; Riedel, 2000), was used to model the ground. This model is particularly useful for modeling the dynamic loading of brittle materials such as concrete and rock. The RHT model is formulated in such a manner that the input can be scaled with reference to the unconfined compressive strength of a cubic specimen; therefore, the ground can be modeled by that strength.

The present numerical study was carried out under fair-ground conditions. According to Bieniawski (1979), the uniaxial compressive strength of cylindrical specimens under fair-ground conditions is 50-100 MPa. For modeling fair ground, the present study applied the uniaxial compressive strength of 75 MPa, which is the average of 50 MPa and 100 MPa, to the RHT model. The following well-known empirical relationship was used for converting the strength of cylindrical specimens to that of cubic specimens (CEB, 1990; Griffiths & Thom, 2007; Palmström & Nilsen, 2000):

\[ f_{cylinder} = f_{cube} \times CF_s \]  

\( f_{cylinder} \) is the uniaxial compressive strength of cylindrical specimens, \( f_{cube} \) is the uniaxial compressive strength of cubed specimens, \( CF_s \) is the conversion factor for cubic vs. cylindrical specimens (\( CF_s = 0.8 \)).

The uniaxial compressive strength, 93.75 MPa, of cubic specimen, as calculated by Eq. (4), was applied to the RHT model for modeling fair ground. The tensile strength of the ground was one-tenth of its compressive strength, as shown in Table 1. The table presents the parameters of the RHT model used in the present study.
Table 1 Parameters of the RHT model used in the present study (Riedel et al., 1999; Riedel, 2000)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference density</td>
<td>2.75 (g/cm³)</td>
<td>Shear modulus, G</td>
<td>2.206 × 10⁴ (MPa)</td>
</tr>
<tr>
<td>Porous density</td>
<td>2.52 (g/cm³)</td>
<td>Compressible strength, fₐ</td>
<td>93.75 (MPa)</td>
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<td>Porous sound speed</td>
<td>3.242 × 10³ (m/s)</td>
<td>Tensile strength, fₖ / fₐ</td>
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<td>Initial compaction pressure</td>
<td>93.30 (MPa)</td>
<td>Shear strength, fₖ / fₐ</td>
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<td>Solid compaction pressure</td>
<td>6.000 × 10³ (MPa)</td>
<td>Intact failure surface constant, A</td>
<td>1.600</td>
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<tr>
<td>Compaction exponent</td>
<td>3.000</td>
<td>Intact failure surface exponent, N</td>
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<tr>
<td>Bulk modulus, A₁</td>
<td>3.527 × 10⁷ (MPa)</td>
<td>Tens./Comp. meridian ratio, Q₂₀</td>
<td>6.805 × 10⁻¹</td>
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<tr>
<td>Parameter, A₂</td>
<td>3.958 × 10⁷ (MPa)</td>
<td>Brittle to ductile transition, BQ</td>
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<tr>
<td>Parameter, A₃</td>
<td>9.040 × 10⁷ (MPa)</td>
<td>G (elastic)/G (elastic-plastic)</td>
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</tr>
<tr>
<td>Parameter, B₀</td>
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<td>Elastic strength / fₖ</td>
<td>0.700</td>
</tr>
<tr>
<td>Parameter, B₁</td>
<td>1.220</td>
<td>Elastic strength / fₖ</td>
<td>0.530</td>
</tr>
<tr>
<td>Parameter, T₁</td>
<td>3.527 × 10⁴ (MPa)</td>
<td>Residual strength constant, B</td>
<td>1.600</td>
</tr>
<tr>
<td>Parameter, T₂</td>
<td>0.000 (MPa)</td>
<td>Residual strength exponent, M</td>
<td>0.610</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>300 (K)</td>
<td>Compressive strain rate exponent, α</td>
<td>9.090 × 10⁻³</td>
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<tr>
<td>Specific heat</td>
<td>6.540 × 10² (J/kgK)</td>
<td>Compressive strain rate exponent, δ</td>
<td>1.250 × 10⁻²</td>
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<td>Thermal conductivity</td>
<td>0.000 (J/mKs)</td>
<td>Max. fracture strength ratio</td>
<td>1.000 × 10⁻²⁰</td>
</tr>
</tbody>
</table>

3.2 Assessment method for vibration-reduction effect

The effect of the reduction of blast-induced vibration due to line-drilling or bottom-air-deck was investigated by varying the considered parameters, while keeping the other numerical conditions, including the material properties, EOSs, strength model, and boundary conditions, unchanged.

The assessment of the vibration-reduction effect was carried out by comparing the values of the peak vector sum (PVS) between two cases, the one with line-drilling (or bottom-air-deck) and the other without. The vibration-reduction effect, i.e., the amplitude reduction factor, was calculated by using Eq. (5):

$$ARF = \frac{\text{Average} \left( 1 - \frac{V_{\text{no-method}}(D_1)}{V_{\text{method}}(D_1)}, \ldots, 1 - \frac{V_{\text{no-method}}(D_n)}{V_{\text{method}}(D_n)} \right) \times 100}{n}$$

(5)

where $ARF$ (%) is the amplitude reduction factor, i.e., the vibration-reduction effect, $V_{\text{no-method}}$ and $V_{\text{method}}$ are the PVS values (mm/s) of the two cases (without and with line-drilling (or bottom-air-deck), respectively), and $D$ (m) is the distance from the blasting source to the point of monitoring.
3.3 Numerical investigations of the effectiveness of line-drilling method

3.3.1 Effect of the spacing and diameter of drill holes

This analysis focused on assessing the effect of the spacing and diameter of drill holes on the vibration reduction. The region of the analysis was rectangular in shape, 8.35 m long and 3.65 m high. The applied diameters of drill holes were 50, 100, and 150 mm, and the net spacings for each diameter were 50, 150, 250, and 350 mm. The distance between line-drilling and blasthole was 300 mm. Fig. 6 shows a schematic of numerical analysis for assessing the effect of spacing and diameter of drill holes on the vibration reduction, and the configuration of the numerical model, respectively. Fig. 7 shows the vibration-reduction effects for various spacings and diameters of drill holes. From the analysis, the vibration-reduction effect was found to increase with decreasing the spacing of drill holes and with increasing the diameter of those. The following correlation equation between the vibration-reduction effect and drilling condition was derived by regression analysis (Fig. 8).

\[
ARF = 15.260 \cdot \ln\left(\frac{D^2}{S-D}\right) - 25.901, \quad R^2 = 0.986
\]  

(6)

where \(ARF\) (%) is the amplitude reduction factor, \(D\) (mm) is the diameter of drill holes, and \(S\) (mm) is the spacing of drill holes.

Fig. 6 (a) Schematic of numerical analysis for assessing the effect of various spacing and diameter of drill holes on the vibration reduction, and (b) configuration of the numerical model. G is the gauge.
3.3.2 Effect of the number of drill holes and their arrangement

This analysis focused on assessing the effect of the number of rows of drill holes and their arrangement on the vibration reduction. The region of this analysis was the same as that in the Subsection 3.3.1. A double row and triple row of drill holes of 50 mm in diameter were applied and the rows were arranged in a parallel and zigzag manner. The spacing of the drill holes and the rows was 200 mm and the distance between line-drilling and blasthole was 300 mm. Table 2 shows the vibration-reduction effects for the number of rows of drill holes and their arrangement. From the analysis, the vibration-reduction effect was found to increase with increasing the number of rows of drill holes. The vibration-reduction effect of a double row of drill holes with a zigzag configuration was about nine-tenths of that of a triple row of drill holes with a zigzag configuration. The vibration-reduction effect of a triple row of drill holes was almost the same as that of a single row of drill holes with half of the spacing of a triple row of drill holes.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Distance (m)</th>
<th>LD-NO</th>
<th>LD-200-DP</th>
<th>LD-200-DZ</th>
<th>LD-200-TZ</th>
<th>LD-100</th>
</tr>
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<tbody>
<tr>
<td>G1</td>
<td>1.50</td>
<td>3,072.9</td>
<td>2,185.0</td>
<td>2,086.3</td>
<td>2,001.0</td>
<td>1,890.2</td>
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<tr>
<td>G2</td>
<td>2.00</td>
<td>2,299.6</td>
<td>1,637.1</td>
<td>1,567.8</td>
<td>1,510.0</td>
<td>1,442.1</td>
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<tr>
<td>G3</td>
<td>2.50</td>
<td>1,806.0</td>
<td>1,289.8</td>
<td>1,239.2</td>
<td>1,196.5</td>
<td>1,155.4</td>
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<td>G4</td>
<td>3.00</td>
<td>1,456.3</td>
<td>1,044.2</td>
<td>1,005.8</td>
<td>969.7</td>
<td>946.4</td>
</tr>
<tr>
<td>G5</td>
<td>3.50</td>
<td>1,197.2</td>
<td>861.6</td>
<td>831.4</td>
<td>800.9</td>
<td>788.4</td>
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<td>G6</td>
<td>4.00</td>
<td>998.3</td>
<td>722.4</td>
<td>696.2</td>
<td>669.8</td>
<td>665.0</td>
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<td>G7</td>
<td>4.50</td>
<td>842.1</td>
<td>611.3</td>
<td>589.7</td>
<td>565.6</td>
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<td>G8</td>
<td>5.00</td>
<td>717.1</td>
<td>522.8</td>
<td>503.4</td>
<td>482.9</td>
<td>487.1</td>
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<td>G9</td>
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<td>614.5</td>
<td>451.3</td>
<td>431.9</td>
<td>413.4</td>
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<td>G10</td>
<td>6.00</td>
<td>530.9</td>
<td>390.3</td>
<td>373.8</td>
<td>357.2</td>
<td>400.7</td>
</tr>
</tbody>
</table>

| ARF (%) | - | 27.78 | 30.61 | 33.33 | 33.51 |

LD-NO = case without line-drilling; LD-200-DP and LD-200-DZ = cases on a double row of drill holes with a 200 mm spacing in a parallel and zigzag manner, respectively; LD-200-TZ = case on a triple row of drill holes with a 200 mm spacing in a zigzag manner; LD-100 = case on a single row of drill holes with a 100 mm spacing; ARF = amplitude reduction factor
3.3.3 Effect of the distance between blasthole and line-drilling

This analysis was carried out for investigating the effect of the distance between line-drilling and blasthole on the vibration reduction. A double row of drill holes was applied and the spacing of rows was 200 mm. The diameter and spacing of drill holes were 50 mm and 200 mm, respectively. Fig. 9 shows a schematic of numerical analysis and the relationship between the vibration-reduction effect and distance between line-drilling and blasthole. From the analysis, the vibration-reduction effect was found to decrease with increasing the distance between line-drilling and blasthole. Consequently, similar to the result of Woods (1968), active isolation was more effective than passive isolation. From the analysis, the following correlation equation was derived.

\[ ARF = 127.510 \cdot (D_{LD-BH})^{-0.244} \quad R^2 = 0.999 \]  

(7)

where \( ARF \) (\%) is the amplitude reduction factor and \( D_{LD-BH} \) (m) is the distance between line-drilling and blasthole.

![Fig. 9 (a) Schematic of numerical analysis for assessing the effect of the distance between line-drilling and blasthole on the vibration reduction, and (b) relationship between the vibration-reduction effect and distance between line-drilling and blasthole. G is the gauge](image)

3.3.4 Quantitative information on the drilling of barrier holes

Two correlation equations, Eqs. (6) and (7) were derived from the parametric study of line-drilling method and these two equations can be combined to yield quantitative information on the drilling of barrier holes. In order to combine the two equations, Eq. (7) was normalized for the distance between line-drilling and blasthole of 300 mm and Eq. (8) was obtained by combining the two equations. This equation was used for verifying the results of field experiments and for proposing the design conditions of line-drilling for the reduction of blast-induced vibration in the transverse direction of a tunnel.

\[ ARF = \left[ 60.796 \cdot \ln \left( \frac{D^2}{S-D} \right) - 103.190 \right] (D_{LD-BH})^{-0.244} \]

(8)

where \( ARF \) (\%) is the amplitude reduction factor, \( D \) (mm) is the diameter of drill holes, \( S \) (mm) is the spacing of drill holes, and \( D_{LD-BH} \) (mm) is the distance between line-drilling and blasthole.
3.4 Numerical investigations of the effectiveness of bottom-air-deck method

3.4.1 Effect of the length of bottom-air-deck on the vibration reduction

Since bottom-air-deck is applied to each blasthole, it is necessary to assess the effect of the charge weight per delay on the vibration reduction. Therefore, in the present study, two kinds of numerical analyses were carried out in order to investigate the effect of the length of bottom-air-deck on the vibration reduction: numerical analysis of a single blasthole under axial-symmetry conditions; and numerical analysis of a single blasthole under plane-strain conditions.

The present study applied the following conditions, which are commonly practiced for tunnel blasting under fair-ground conditions: the diameter and length of a blasthole were 45 mm and 2.2 m, respectively; and the amount of emulsion-type explosives was 1.0 kg. As stated earlier, TNT was used in the present study as a source of explosion and the amount of explosive was calculated by the empirical equation for the relative weight strength, i.e., Eq. (3). The length and diameter of 0.782 kg of TNT, as calculated by Eq. (3), were 1.0 m and 25 mm, respectively.

Fig. 10 shows a schematic of numerical analysis for a single blasthole under axial-symmetry conditions and the configuration of the numerical model for assessing the vibration-reduction effect of bottom-air-deck. The region of analysis was cylindrical in shape, 13.0 m in length and 10.0 m in radius. The applied lengths of bottom-air-deck were 100, 200, 300, 400, and 500 mm. The mechanical strength of the paper-tube used for bottom-air-deck is negligible when compared with the detonation pressure of TNT and the strength of the ground. Therefore, the bottom-air-deck was modeled by leaving an empty space.

The present study investigated the effect of the charge weight per delay on the vibration reduction through the numerical analysis of a single blasthole under plane-strain conditions. The plane-strain condition means that blastholes are drilled continuously without any spacing between them. Therefore, this condition can be regarded as one that maximizes the effect of the charge weight per delay on the vibration reduction. Fig. 11 shows a schematic of numerical analysis and the configuration of the numerical model for a single blasthole under plane-strain conditions for assessing the vibration-reduction effect of bottom-air-deck. The region of analysis was rectangular in shape, 26.0 m long and 14.0 m high.

![Fig. 10](image-url) (a) Schematic of numerical analysis under axial-symmetry conditions for assessing the vibration-reduction effect of bottom-air-deck, and (b) configuration of the numerical model. G is the gauge.
Table 3 summarizes the vibration-reduction effects for various lengths of bottom-air-deck in the numerical analyses under axial-symmetry conditions. From the analyses, the vibration-reduction effects in the cases where the bottom-air-deck had lengths of 100, 200, 300, 400, and 500 mm were 12.0, 18.6, 24.5, 30.8, and 35.7%, respectively. Second, Table 4 summarizes the vibration-reduction effects for various lengths of bottom-air-deck in the numerical analyses under plane-strain conditions. From the analyses, the vibration-reduction effects in the cases where the bottom-air-deck had lengths of 100, 200, 300, 400, and 500 mm were 3.9, 8.4, 9.9, 14.5, and 15.0%, respectively. Similar to the previous numerical analyses under axial-symmetry conditions, as the bottom-air-deck lengthened, the vibration-reduction effect tended to increase.

The vibration-reduction effects from the numerical analyses under axial-symmetry conditions were found to be greater than the corresponding results for plane-strain conditions, owing to the effect of the charge weight per delay. The vibration-reduction effects in the numerical analyses under both axial-symmetry and plane-strain conditions could be regarded as the maximum and minimum vibration-reduction effects of the bottom-air-deck, respectively, under fair-ground conditions. Consequently, it is believed that for the bottom-air-decks of lengths of 100, 200, 300, 400, and 500 mm, vibration-reduction effects of 3.9-12.0%, 8.4-18.6%, 9.9-24.5%, 14.5-30.8%, and 15.0-35.7%, respectively, can be expected.
### Table 3 Summary of the vibration-reduction effects for various lengths of bottom-air-deck in the numerical analyses under axial-symmetry conditions

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Distance (m)</th>
<th>AD-NO</th>
<th>AD-100</th>
<th>AD-200</th>
<th>AD-300</th>
<th>AD-400</th>
<th>AD-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>3.00</td>
<td>39.45</td>
<td>33.14</td>
<td>29.34</td>
<td>27.76</td>
<td>23.11</td>
<td>21.56</td>
</tr>
<tr>
<td>G2</td>
<td>3.25</td>
<td>27.23</td>
<td>23.13</td>
<td>21.72</td>
<td>20.60</td>
<td>18.52</td>
<td>16.78</td>
</tr>
<tr>
<td>G3</td>
<td>3.50</td>
<td>22.91</td>
<td>19.72</td>
<td>18.49</td>
<td>17.53</td>
<td>15.90</td>
<td>14.41</td>
</tr>
<tr>
<td>G4</td>
<td>3.75</td>
<td>19.46</td>
<td>16.91</td>
<td>15.20</td>
<td>14.30</td>
<td>12.52</td>
<td>11.64</td>
</tr>
<tr>
<td>G5</td>
<td>4.00</td>
<td>16.52</td>
<td>14.47</td>
<td>13.08</td>
<td>12.19</td>
<td>10.76</td>
<td>10.07</td>
</tr>
<tr>
<td>G6</td>
<td>4.25</td>
<td>12.12</td>
<td>10.70</td>
<td>10.05</td>
<td>9.44</td>
<td>8.70</td>
<td>8.03</td>
</tr>
<tr>
<td>G7</td>
<td>4.50</td>
<td>10.44</td>
<td>9.27</td>
<td>8.72</td>
<td>8.11</td>
<td>7.54</td>
<td>6.99</td>
</tr>
<tr>
<td>G8</td>
<td>4.75</td>
<td>8.93</td>
<td>7.96</td>
<td>7.23</td>
<td>6.65</td>
<td>6.10</td>
<td>5.72</td>
</tr>
<tr>
<td>G9</td>
<td>5.00</td>
<td>7.70</td>
<td>6.90</td>
<td>6.27</td>
<td>5.76</td>
<td>5.33</td>
<td>4.99</td>
</tr>
<tr>
<td>G10</td>
<td>5.25</td>
<td>5.86</td>
<td>5.29</td>
<td>4.97</td>
<td>4.59</td>
<td>4.37</td>
<td>4.07</td>
</tr>
<tr>
<td>G11</td>
<td>5.50</td>
<td>5.10</td>
<td>4.60</td>
<td>4.33</td>
<td>4.00</td>
<td>3.81</td>
<td>3.55</td>
</tr>
<tr>
<td>G12</td>
<td>5.75</td>
<td>4.33</td>
<td>3.85</td>
<td>3.57</td>
<td>3.24</td>
<td>3.07</td>
<td>2.88</td>
</tr>
<tr>
<td>G13</td>
<td>6.00</td>
<td>3.65</td>
<td>3.26</td>
<td>3.09</td>
<td>2.76</td>
<td>2.65</td>
<td>2.48</td>
</tr>
</tbody>
</table>

**ARF (%)** - 12.0 18.6 24.5 30.8 35.7

AD-NO = case without bottom-air-deck; AD-100, AD-200, AD-300, AD-400, and AD-500 = cases of bottom-air-decks with lengths of 100, 200, 300, 400, and 500 mm, respectively; ARF = amplitude reduction factor

### Table 4 Summary of the vibration-reduction effects for various lengths of bottom-air-deck in the numerical analyses under plane-strain conditions

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Distance (m)</th>
<th>AD-NO</th>
<th>AD-100</th>
<th>AD-200</th>
<th>AD-300</th>
<th>AD-400</th>
<th>AD-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>2.50</td>
<td>1,590.90</td>
<td>1,545.40</td>
<td>1,422.20</td>
<td>1,378.30</td>
<td>1,313.20</td>
<td>1,271.40</td>
</tr>
<tr>
<td>G2</td>
<td>3.50</td>
<td>1,150.00</td>
<td>1,126.40</td>
<td>1,034.10</td>
<td>1,000.60</td>
<td>951.19</td>
<td>938.88</td>
</tr>
<tr>
<td>G3</td>
<td>4.50</td>
<td>877.59</td>
<td>856.57</td>
<td>789.27</td>
<td>765.83</td>
<td>721.84</td>
<td>720.80</td>
</tr>
<tr>
<td>G4</td>
<td>5.50</td>
<td>688.60</td>
<td>665.03</td>
<td>615.37</td>
<td>602.20</td>
<td>564.49</td>
<td>564.00</td>
</tr>
<tr>
<td>G5</td>
<td>6.50</td>
<td>547.53</td>
<td>524.41</td>
<td>488.99</td>
<td>480.43</td>
<td>451.85</td>
<td>450.21</td>
</tr>
<tr>
<td>G6</td>
<td>7.50</td>
<td>440.40</td>
<td>421.53</td>
<td>392.97</td>
<td>387.12</td>
<td>363.95</td>
<td>362.74</td>
</tr>
<tr>
<td>G7</td>
<td>8.50</td>
<td>359.19</td>
<td>339.32</td>
<td>319.03</td>
<td>314.26</td>
<td>295.96</td>
<td>294.54</td>
</tr>
<tr>
<td>G8</td>
<td>9.50</td>
<td>291.94</td>
<td>273.67</td>
<td>259.38</td>
<td>257.66</td>
<td>243.61</td>
<td>243.09</td>
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<tr>
<td>G9</td>
<td>10.50</td>
<td>238.64</td>
<td>224.19</td>
<td>217.54</td>
<td>213.42</td>
<td>199.95</td>
<td>199.95</td>
</tr>
<tr>
<td>G10</td>
<td>11.50</td>
<td>195.97</td>
<td>188.67</td>
<td>185.51</td>
<td>185.10</td>
<td>178.92</td>
<td>178.34</td>
</tr>
<tr>
<td>G11</td>
<td>12.50</td>
<td>175.01</td>
<td>169.69</td>
<td>167.35</td>
<td>166.39</td>
<td>159.63</td>
<td>158.81</td>
</tr>
<tr>
<td>G12</td>
<td>13.50</td>
<td>155.17</td>
<td>151.07</td>
<td>148.03</td>
<td>146.42</td>
<td>141.48</td>
<td>141.55</td>
</tr>
<tr>
<td>G13</td>
<td>14.50</td>
<td>137.77</td>
<td>132.76</td>
<td>132.31</td>
<td>130.83</td>
<td>124.94</td>
<td>124.97</td>
</tr>
<tr>
<td>G14</td>
<td>15.50</td>
<td>121.75</td>
<td>116.63</td>
<td>114.72</td>
<td>113.07</td>
<td>107.21</td>
<td>106.56</td>
</tr>
</tbody>
</table>

**ARF (%)** - 3.9 8.4 9.9 14.5 15.0

AD-NO = case without bottom-air-deck; AD-100, AD-200, AD-300, AD-400, and AD-500 = cases of bottom-air-decks with lengths of 100, 200, 300, 400, and 500 mm, respectively; ARF = amplitude reduction factor
3.4.2 Effect of the length of bottom-air-deck on the excavation efficiency

The present study investigated the effect of the length of bottom-air-deck on the excavation efficiency through the numerical analysis of a single blasthole under axial-symmetry conditions. Fig. 12 shows a schematic of numerical analysis for a single blasthole under axial-symmetry conditions for assessing the excavation efficiency of bottom-air-deck, besides the configuration of the numerical model. The region of analysis was cylindrical in shape, 3.2 m in length and 500 mm in radius. According to Jimeno et al. (1995), the specific charge (charge weight per unit volume) required for excavating medium-strength rocks in bench blasting is 0.3-0.6 kg/m$^3$. In the present study, it was assumed that the medium-strength rocks mentioned by Jimeno et al. (1995) could be regarded as the fair-ground that is considered in the present study. Therefore, the specific charge of 0.45 kg/m$^3$, which is the mid-point of the range of the required specific charge as per (Jimeno et al., 1995), was used. Correspondingly, the burden used in the numerical analysis was 500 mm, as shown in Fig. 12. The applied lengths of bottom-air-deck were 100, 200, 300, 400, and 500 mm. The bottom-air-deck was modeled by leaving an empty space, as previously modeled. All the materials, including TNT, the ground, and the stemming material, were modeled using SPH in consideration of the large deformation of the materials during the computation.

The excavation efficiency was assessed by the following equation:

$$EE = \frac{L_{\text{advance}}}{L_{\text{drilling}}} \times 100$$

where $EE$ (%) is the excavation efficiency through blasting and $L_{\text{advance}}$ and $L_{\text{drilling}}$ are the advance and the drilling length (m) of a blasthole, respectively.

Since the RHT model can simulate the damage to a material that is caused by dynamic loading, a certain damaged region of the surrounding ground, which can be scaled after blasting, can be included in the calculation of the advance. However, it is difficult to numerically determine a quantitative criterion of the damage index to distinguish whether or not a damaged region can be scaled. Therefore, the advance was assessed by measuring the shortest distance from the top of a blasthole to the ground that is left after blasting. Fig. 13 shows the advance for various lengths of bottom-air-deck. From the analyses, the reductions in the advance in the cases where the bottom-air-decks were 100, 200, 300, 400, and 500 mm long, were 70, 221, 286, 404, and 497 mm, respectively. From the results, the reduction in the advance was found to be approximately proportional to the length of bottom-air-deck. However, the actual reduction in the advance in the field is expected to be less than the predicted value owing to the exclusion from the calculation of a certain damaged region of the surrounding ground. From the numerical analyses, it was identified that the vibration reduction can be expected in the direction of tunnelling owing to bottom-air-deck but the excavation efficiency through blasting can be reduced.
Fig. 12 (a) Schematic of numerical analysis for assessing the excavation efficiency of bottom-air-deck, and (b) configuration of the numerical model.

Fig. 13 Advances for various lengths of bottom-air-deck
4. FIELD EXPERIMENTAL STUDY

4.1 Assessment method for vibration-reduction effect

In the numerical study, it was possible to monitor blast-induced vibrations in both cases, viz., with and without a vibration-reduction method under the same direction of monitoring and the same distance from the source of blasting. However, in the field experiment, it is not always possible to monitor blast-induced vibrations under such controls. Therefore, in the present experimental study, the vibration-reduction effect of line-drilling and bottom-air-deck was assessed by comparing the values of PVS between the two cases, as calculated through the ground-attenuation equations of the respective cases. It is important to note that since a ground-attenuation equation is obtained from regression analysis, it is only valid within the range of the sample data. Therefore, by using the following equation, the vibration-reduction effect was assessed within the range of overlap of the sample data for the two cases:

\[
ARF = \frac{\text{Average} \left(1 - \frac{V_{\text{no-method}}(SD_1)}{V_{\text{method}}(SD_1)}\right) \times \left(1 - \frac{V_{\text{no-method}}(SD_2)}{V_{\text{method}}(SD_2)}\right)}{100}
\]

where \(ARF\) (%) is the amplitude reduction factor, \(V_{\text{no-method}}\) and \(V_{\text{method}}\) are the calculated PVS values (mm/s) of the two cases (without and with a vibration-reduction method, respectively), and \(SD_1\) and \(SD_2\) are the minimum and maximum scaled distance for assessing the vibration-reduction effect, respectively.

4.2 Field experiments of line-drilling method

4.2.1 Single-hole experiment

The single-hole experiment for assessing the vibration-reduction effect of a single row of drill holes with a 300 mm spacing was carried out at Yeongwol limestone quarry in Korea. Fig. 14 shows a schematic of experiment layout in the field. The elastic modulus and the uniaxial compressive and tensile strengths of rock at the site were 50.4 GPa, 178.4 MPa, and 12.7 MPa, respectively. The diameter and length of drill holes and blastholes were 45 mm and 2.2 m, respectively. An emulsion-type explosive of 0.625 kg/hole was used. A total of 12 single-hole experiments were carried out: six experiments without line-drilling; and six experiments with the line-drilling. Fig. 15 shows the ground vibration results of the two cases and the derived ground-attenuation equations.

Ground attenuation equations:

\[
V_{LD-NO} = 156.60 \cdot SD_2^{-1.12}, R^2 = 0.624
\]

\[
V_{LD-300} = 90.89 \cdot SD_2^{-1.04}, R^2 = 0.550
\]

where \(V_{LD-NO}\) and \(V_{LD-300}\) are the PVSs (mm/s) of the cases without line-drilling and on a single row of drill holes with a 300 mm spacing, respectively, and \(SD_2\) is the square-root scaled distance (m/kg\(^{1/2}\)).

The vibration-reduction effect in the case on a single row of drill holes with a 300 mm spacing was 16.48%. The dark area indicated in Fig. 16 denotes the range of the scaled distance for investigating the vibration-reduction effect. The vibration-reduction effect predicted by Eq. (8) was 5.66% under the
conditions of this field experiment. The result of the field experiment was found to be greater than that predicted through the numerical analysis. This difference is believed to be due to the effect of discontinuities in rock masses.

Fig. 14 Schematic of experiment layout in the field. LD-NO and LD-300 are the cases without line-drilling and on a single row of drill holes with a 300 mm spacing, respectively.

Fig. 15 Peak vector sum vs. scaled distance
4.2.2 Full-scale experiment

The full-scale experiment for assessing the vibration-reduction effect on a double row of drill holes with a 200 mm spacing was carried out at Duhak railway tunnel in Korea. Fig. 16(a) shows a plan view of the field experiment site and the blasting pattern. The elastic modulus and the uniaxial compressive and tensile strengths of rock at the site were 76.2 GPa, 98.0 MPa, and 6.8 MPa, respectively. The ground condition based on the RMR (rock mass rating) was fair. The diameter of blastholes and drill holes was 45 mm, with the lengths of blastholes and drill holes being 1.1~2.2 m and 10.0 m, respectively. The maximum charge weight per delay was 0.4~0.9 kg/delay. A total of three full-scale experiments were carried out. Fig. 16(b) shows the ground vibration results of the two cases and the derived ground-attenuation equations.

Ground attenuation equations:

\[ V_{LD-NO} = 1,331.07 \cdot S^{1.34}, R^2 = 0.560 \]  \hspace{1cm} (13)

\[ V_{LD-200-DZ} = 372.31 \cdot S^{-1.17}, R^2 = 0.919 \]  \hspace{1cm} (14)

where \( V_{LD-NO} \) and \( V_{LD-200-DZ} \) are the PVSs (mm/s) of the cases without line-drilling and on a double row of drill holes with a 200 mm spacing in a zigzag manner, respectively, and \( S \) is the square-root scaled distance (m/kg\(^{1/2}\)).

The vibration-reduction effect in the case on a double row of drill holes with a 200 spacing in a zigzag manner was 16.48%. The vibration-reduction effect predicted by Eq. (8) was 14.61% under the conditions of this field experiment. The result of the field experiment was found to be greater than that predicted through the numerical study. This difference is believed to be due to the effect of discontinuities in rock masses as well as the difference of the ground condition between the two cases; the topography showed that the soil layer in the regions without line-drilling was thicker than that in the regions with the line-drilling.

![Fig. 16 (a) Plan view of the field experiment site, and (b) Peak vector sum vs. scaled distance. LD-NO and LD-200-DZ are the cases without line-drilling and on a double row of drill holes with a 200 mm spacing in a zigzag manner, respectively. G is the gauge. The dark area denotes the range of the scaled distance for investigating the vibration-reduction effect.](image)
4.3 Field experiments of bottom-air-deck method

4.3.1 Effect of the length of bottom-air-deck on the vibration reduction

(1) Single-hole experiment

The single-hole experiment was carried out at a granite quarry in Korea. Fig. 17 shows a schematic of the experimental layout. A total of three single-hole experiments on bottom-air-decks that were 100, 200, and 300 mm in length, were carried out. The elastic modulus and the uniaxial compressive strength of rock at the site were 53.1 GPa and 162.0 MPa, respectively. The blastholes were drilled in the horizontal direction. The spacing and the burden of blastholes were 1.0-1.5 m and 1.0 m, respectively, with the blastholes being 2.2 m in length and 45 mm in diameter. An emulsion-type explosive of 0.5 kg/hole was used. A total of 24 geophones were arranged in the direction of drilling, as shown in Fig. 17. The vibration-reduction effect was assessed by using the existing ground-attenuation equation (Eq. (15)), which was derived during production blasting in the field and the range of the sample data was 20-50 m.

Fig. 18 shows the ground-vibration results and the derived ground-attenuation equations.

Case without bottom-air-deck:

\[ V = 1,809.30(SD_2)^{-1.54} \]  

Case with bottom-air-deck at a length of 100 mm:

\[ V = 4,767.60(SD_2)^{-1.88} , R^2 = 0.730 \]  

Case with bottom-air-deck at a length of 200 mm:

\[ V = 5,400.08(SD_2)^{-1.95} , R^2 = 0.754 \]  

Case with bottom-air-deck at a length of 300 mm:

\[ V = 6,103.80(SD_2)^{-2.09} , R^2 = 0.770 \]

In the above, \( V \) is the PVS (mm/s) and \( SD_2 \) is the square-root scaled distance (m/kg^{1/2}).

The vibration-reduction effects in the case of bottom-air-decks with lengths of 100, 200, and 300 mm were 28.8, 38.4, and 59.8%, respectively. The vibration-reduction effects calculated in this experiment were found to be greater than those predicted through the numerical study. The differences in the vibration-reduction effects between the numerical and experimental studies are believed to be caused by using the existing ground-attenuation equation, which was derived under field conditions that were different from the cases with bottom-air-decks. However, similar to the results of the numerical study, as the bottom-air-deck lengthened, the vibration-reduction effect tended to increase.

In addition, the normalized vibration-reduction effects in the cases of bottom-air-decks with lengths of 100, 200, and 300 mm were 12.0, 16.0, and 24.9%, respectively. The normalization assumed that for a length of 100 mm, the vibration-reduction effect obtained from the field experiment is equal to 12.0%, the value that was predicted through numerical analysis. These normalized vibration-reduction effects were found to be quite close to the maximum vibration-reduction effects of the bottom-air-deck that were predicted through the numerical analyses of a single blasthole under axial-symmetry conditions. From the single-hole experiment, the numerical and experimental results were found to agree well with each other.
Fig. 17 Schematic of the experimental layout for bottom-air-deck in the field.

Fig. 18 Peak vector sum vs. the square-root scaled distance. AD-NO is the case without bottom-air-deck. AD-100, AD-200, and AD-300 are the cases of bottom-air-decks with lengths of 100, 200, and 300 mm, respectively. The dark area denotes the range of the scaled distance for investigating the vibration-reduction effect.
(2) Full-scale experiment

The full-scale experiment was carried out at the tunnel site of the Geondong limestone mine in Korea. Fig. 19(a) shows a plan view of the field experiment site and the blasting pattern. A total of six full-scale experiments were carried out: three experiments without bottom-air-deck and three experiments with the bottom-air-deck at a length of 200 mm. The elastic modulus and the uniaxial compressive and tensile strengths of rock at the site were 43.5 GPa, 83.5 MPa, and 4.9 MPa, respectively. The ground condition based on the result of face mapping was fair. The diameter of blastholes was 45 mm and their drilling length was 3.0 m in the direction of tunnelling. Powdery ANFO (ammonium nitrate fuel oil) explosive was used as the column explosive with one cartridge explosive of the emulsion-type being used as a primer. The amount of explosives per blasthole was 2.2-3.0 kg/hole. Ten V-cut blastholes were initiated simultaneously. Thus, the maximum charge weight per delay was 22.0-33.0 kg/delay. A total of four geophones were arranged in the direction of tunnelling, as shown in Fig. 19(a). Fig. 19(b) shows the ground-vibration results and the derived ground-attenuation equations.

Case without bottom-air-deck:

\[ V = 10,256.52 (SD_2)^{-2.29}, R^2 = 0.815 \]  

Case with bottom-air-deck at a length of 200 mm:

\[ V = 20,234.85 (SD_2)^{-2.57}, R^2 = 0.647 \]  

In the above, \( V \) is the PVS (mm/s) and \( SD_2 \) is the square-root scaled distance (m/kg\(^{1/2}\)).

The vibration-reduction effect in the case of the bottom-air-deck with a length of 200 mm was 9.3% in the range of 15.84-18.22 m/kg\(^{1/2}\) of the square-root scaled distance. The vibration-reduction effect obtained from this experiment was found to be close to the minimum value of 8.4% that was predicted through the numerical study. This result is believed to be due to the effect of the charge weight per delay since the drilling length of blastholes in the field experiment was longer than that in the numerical analysis and the ten V-cut blastholes were initiated simultaneously. From the full-scale experiment, the numerical and experimental results were found to agree well with each other.

![Diagram](a)  

**Fig. 19** (a) Plan view of the field experiment site, and (b) peak vector sum vs. the square-root scaled distance. AD-NO is the case without bottom-air-deck and AD-200 is the case with a bottom-air-deck of length 200 mm. The dark area denotes the range of the scaled distance for investigating the vibration-reduction effect.
4.3.2 Effect of the length of bottom-air-deck on the excavation efficiency

The full-scale experiment was carried out at the railway tunnel site of the Jecheon-Ssangyong No. 1 construction section in Korea. Fig. 20 shows a plan view of the field experiment site. The experiment was carried out at two sites of Songhak tunnel, as shown in Fig. 20. A total of three full-scale experiments on the bottom-air-deck with a length of 200 mm were carried out: two experiments at site 1; and one experiment at site 2. All the blastholes, except for the contour blastholes, had the bottom-air-deck with a length of 200 mm. The elastic modulus and the uniaxial compressive and tensile strengths of rock at the site were 76.2 GPa, 98.0 MPa, and 6.8 MPa, respectively. The ground condition based on the RMR was fair. The diameter of blastholes was 45 mm and their designed drilling length was 4.0 m in the direction of tunnelling. An emulsion-type explosive of 2.8 kg/hole was used.

For investigating the advance after blasting, the stations of the tunnel face at the four points shown in Fig. 21 were surveyed. The advance was the difference between the averages of the stations before and after blasting. The excavation efficiency was assessed by Eq. (9). The excavation efficiency in the case without the bottom-air-deck was investigated on the basis of the daily report available at the site.

The average excavation efficiencies in the cases both with and without the bottom-air-deck were 84.5% and 88.8%, respectively. The reduction in the advance was found to be approximately 172 mm. The reduction in the advance in the field experiment was found to be smaller than the numerically predicted value of 221 mm. The difference is attributable to not considering damaged region around the blasthole in the calculation of the advance in the numerical study. From the experiment, the reduction in the advance was found to be approximately proportional to the length of the bottom-air-deck. The numerical and experimental results were found to agree well with each other.

Fig. 20 Plan view of the field experiment site

Fig. 21 Measurement of the station of the tunnel face for investigating the advance. The symbols, MP 1 through MP 4, are the points for measuring the stations of the tunnel face.
5. DESIGN CONDITIONS FOR FIELD APPLICATION

From the comparison between the numerical and experimental results, good agreement was found. It is believed that the vibration-reduction effects predicted through the numerical study can be expected when both methods are applied to real tunneling practices. The factor of safety in structural and geotechnical engineering typically belongs to the range 1.2-2.0. Assuming that we have detailed information to design the bottom-air-deck through experimental and numerical works, the present study proposes the design condition for the factor of safety of 1.2.

5.1 Design conditions of line-drilling method

In order to propose the design conditions of line-drilling method, the correlation equation, Eq. (8) derived from the numerical study of line-drilling method was used. The following drill conditions were applied in consideration of the constructability of drilling work: the diameter of drill holes = 45 mm; the spacing of those = min. 200 mm; and the number of rows of drill holes = 1 to 2. Table 5 shows the design conditions of line-drilling method for reducing blast-induced vibrations in the transverse direction of a tunnel.

Table 5 Design conditions of line-drilling method

<table>
<thead>
<tr>
<th>Ground condition</th>
<th>Design conditions</th>
<th>Vibration-reduction effect</th>
<th>Predicted</th>
<th>Designed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fair</td>
<td>D (mm) 45 S (mm) 200 DLD-BH 300</td>
<td>Single row</td>
<td>13.19%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>D (mm) 45 S (mm) 250 DLD-BH 300</td>
<td>Double row with a zigzag configuration (Spacing of rows = 200 mm)</td>
<td>20.87%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>D (mm) 45 S (mm) 200 DLD-BH 300</td>
<td>Double row with a zigzag configuration (Spacing of rows = 200 mm)</td>
<td>25.97%</td>
<td>20%</td>
</tr>
</tbody>
</table>

D and S = diameter and spacing of drill holes, respectively; DLD-BH = distance between line-drilling and blasthole

5.2 Design conditions of bottom-air-deck method

From the present study, bottom-air-deck was found to reduce ground vibration as well as the excavation efficiency. Therefore, it is necessary to compare the vibration-reduction effects between bottom-air-deck method and the conventional method of reducing the advance per round. Based on the ground-attenuation equation derived in the field, the vibration-reduction effect of the method of reducing the advance per round can be calculated by the following equation:

$$ARF = \left[1 - \left(\frac{SD_2}{SD_1}\right)^n\right] \times 100$$

(21)

where $ARF$ is the amplitude reduction factor, $SD_1$ and $SD_2$ are the square-root scaled distances in the two cases (without and with the reduction in the advance per round, respectively), and $n$ is the constant in Eq. (1).
The comparison of the vibration-reduction effects between bottom-air-deck method and the method of reducing the advance per round was carried out under the following conditions. The well-known range of -3.0 to -1.0 was used for $n$ for the ground-attenuation equation. The drilling length of blasthole was 2.2 m with a 1.0 kg emulsion-type explosive. The distance from the source of blasting to the point of monitoring in the absence of the reduction in the advance per round was 30.0 m.

Fig. 22 shows the results of comparison of the vibration-reduction effects between bottom-air-deck method and the method of reducing the advance per round. In Fig. 22, $n$ is the constant in Eq. (1), and ARF\(_1\) and ARF\(_2\) are the amplitude reduction factors for the method of reducing the advance per round and bottom-air-deck method, respectively.

From the comparison, the vibration-reduction effect of bottom-air-deck method was found to be greater than that of the method of reducing the advance per round. However, when $n$ was -3.0 and both the length of bottom-air-deck and the reduction in the advance per round were 500 mm, the vibration-reduction effects of both methods were almost the same, as shown in Fig. 22. Therefore, the present study did not propose that the bottom-air-deck be 500 mm long. Table 6 shows the design conditions of bottom-air-deck method that have been proposed for reducing blast-induced vibrations in the direction of tunnelling. Since the vibration-reduction effects used for proposing the design conditions were based on the results of numerical analyses for a single blasthole (ignoring the effect of the charge weight per delay), the blast initiation that employs one hole per delay was proposed.

**Table 6** Design conditions of bottom-air-deck method

<table>
<thead>
<tr>
<th>Design conditions</th>
<th>Vibration-reduction effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ground condition</strong></td>
<td><strong>Drilling length &amp; blast initiation</strong></td>
</tr>
<tr>
<td>Fair</td>
<td>2.2 m and blast initiation that employs one hole per delay</td>
</tr>
<tr>
<td></td>
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</table>

The predicted vibration-reduction effects were based on the results of numerical analyses for a single blasthole, not considering the effect of the charge weight per delay.

\(^a\) The value was determined by applying a factor of safety of 1.2 to the predicted vibration-reduction effect.
6. CONCLUSIONS AND DISCUSSION

In the present paper, a quantitative assessment of the effectiveness of line-drilling and bottom-air-deck method was carried out through numerical and experimental study. The results obtained from the numerical and experimental study were as follows.

From the parametric numerical study of line-drilling method, a correlation equation of vibration-reduction effect which gives quantitative information on the drilling of barrier holes was derived. From the parametric numerical study of bottom air-deck method, the ranges of vibration-reduction effects for various lengths of bottom-air-deck were obtained. The reduction in excavation efficiency occurred due to bottom-air-deck and the reduction in advance was approximately proportional to the length of bottom-air-deck. In order to verify the numerical results of both methods, field experiments were carried out. Good agreement was found from a comparison between the numerical and experimental results. From the comparison, it was concluded that when both methods are applied to tunnelling sites, the vibration-reduction effects that were predicted through the numerical study can be expected.

On the basis of the conclusion, design conditions of both methods for the reduction of vibration in the transverse direction of a tunnel and in the direction of tunnelling, respectively, were proposed by introducing the concept of factor of safety. Specifically, the factor of safety of 1.2 was applied with regard to the vibration-reduction effects predicted through the numerical study. For proposing the design conditions of bottom-air-deck method, a comparison of the effectiveness between bottom-air-deck method and the method of reducing the advance per round was carried out. From the comparison, the method with a bottom-air-deck of below 400 mm in length was found to be more effective than the conventional method of reducing the advance per round.

In conclusion, the numerical results were in good agreement with the experimental results. The parametric numerical analyses and field observations suggest that both line-drilling and bottom-air-deck reduce blast-induced ground vibration in the transverse direction of a tunnel and in the direction of tunnelling, respectively. It is believed that vibration-reduction effects of 10-20% and 10-25% in the transverse direction of a tunnel and in the direction of tunnelling, respectively, can be expected under the design conditions proposed in the present study.

Finally, the present experimental study was carried out in only a few sites. Therefore, in future, further field evaluations of the effectiveness of both methods under various conditions of the ground and blasting are needed to extend the engineering application.
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