Article

Excess attenuation of blast sounds propagating over hilly regions and evaluation of the sounds from viewpoints of occupational health and psychological reaction

Hiroyuki Imaizumi*†, Yasumori Takahashi*, Takehiro Isei**, Eishi Kuroda***, Yoshio Nakayama***, Sadashige Horiguchi***, and Masatake Yoshida***

*Institute for Geo-Resources and Environment, National Institute of Advanced Industrial Science and Technology (AIST), 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, JAPAN
†corresponding author: hiroyuki.imaizumi@aist.go.jp

**Vietnam Coal Mine Firedamp Gas Management Center, Phuong Trung Vuong, Uong Bi Town, Quang Ninh, VIETNAM

***Research Center for Explosion Safety, National Institute of Advanced Industrial Science and Technology (AIST), Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, JAPAN

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Abstract

This study examined the Three-Straight-Line model, which was proposed by Isei *et al*. for the excess attenuation of blast sounds propagating over hilly regions, by using newly collected data obtained from several field measurements in areas with varied terrain. Effects of the blast sounds propagated over hilly regions were also studied by comparison with the criterion governing impulsive noises in the workplace as well as in relation to the psychological reactions of human beings to sonic booms. Excess attenuations measured up to about 2.5 km across varied hilly terrain mostly agreed with those predicted by the Three-Straight-Line model. Frequencies at which the attenuation clear appeared tended to become lower with longer range propagation, probably because the acoustic surface and acoustic ground waves of the blast sounds were more attenuated during long-range propagation over uneven terrain. Peak sound pressure levels of the blast sounds at the measuring points ranged from 110 to 160 dB, and most of the blasts were below the level of the hearing-protective criteria governing impulsive noises in the workplace, except close to the blasting point. In addition, when psychological reactions to sonic booms were compared with peak sound pressure levels of the blast sounds, those levels measured at distances of more than 1 km were classified into the categories “tolerable” or “no unpleasantness.” According to these indices, the blast sounds measured in the field seemed to have only slight effects from the occupational health and psychological points of view.

Keywords: Blast, Impulsive noise, Excess attenuation, Three-Straight-Line model, Outdoor sound propagation, Hilly region, Sonic boom

1. Introduction

Blasting operations are used worldwide, especially in mining and engineering work, because mining by blasting is much more efficient than other methods. The noise that is generated from the blasting operations generally consists of impulsive sounds of short duration with a high sound pressure. Because the blast sounds predominantly involve low-frequency components and therefore propagate at longer distances, complaints due to the perception of the low-frequency sounds and/or rattling of building fittings are sometimes occurred.

Most blasting operations are carried out in hilly regions. Therefore, attenuation of the blast sounds is influenced mostly by meteorological conditions[1), 2)], ground-surface characteristics, and the topography[3)] of the propagation paths. Among these factors, the atmospheric absorption[4)] and the ground effects[5] are relatively small, because the primary components of the blast sounds are at low frequencies. Consequently, the gradients of both atmospheric temperature and wind-speed above the ground surface and topography are more important during blast sound propagation. With respect to the effect of topography, Isei *et al.*[3] investigated the excess attenuation of blast sounds during long-range propagation over hilly lands and presented a model in which the excess attenuation versus frequency is approximately described by three straight lines.

There are presently no international regulations concerning low-frequency sounds, although several countries have individually established recommendations or guidelines[6, 7]. In Japan, methods have been developed for estimating the occurrence of complaints in relation to psychological and physical phenomena associated with continuous low-frequency sound/infrasound at receiving points[8, 9]. In addition, impulsive sounds from artillery fire have been evaluated using the parameters L_{CE} and L_{Cden} with reference to the environmental standards governing airplane noise[10]. With respect to other evaluations, allowable sound pressure levels to prevent hearing loss in workers due to exposure to impulsive noise in the workplace have been defined by the Japan Society for Occupational Health[11] and we have used the resulting criteria in this study. Furthermore, the sound pressure levels generated by sonic booms have been compared with the psychological reactions of human beings exposed to those sounds[12]. Nevertheless, there are no clear criteria or standards by which to evaluate the environmental impact on the surrounding areas of impulsive low-frequency sounds such as the blast sounds.

In this study, we examine the Three-Straight-Line propagation model for attenuation of the blast sounds propagated over hilly regions by using data newly obtained from several field measurements in hilly regions with varied terrain. Next, we compare the measurements with the hearing-protective criteria governing impulsive noises in workplaces as well as with the reactions of human beings to sonic booms, in order to investigate effects of the blast sounds on the surrounding areas. Finally, we describe the relationship between the peak sound pressure levels, which are used in the evaluation methods as noise indices, and the excess attenuation observed.

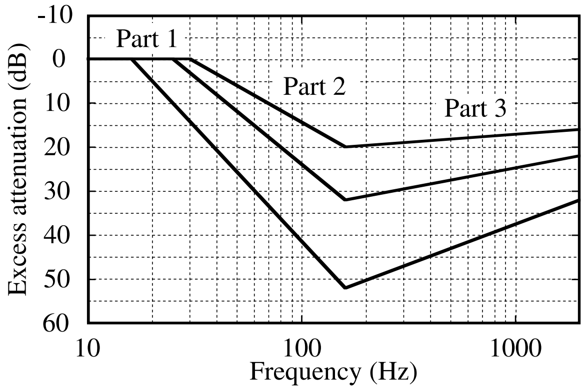

Fig. 1 General features of Three-Straight-Line model.

2. Three-Straight-Line model

In order to investigate the effect of topography on long-range outdoor propagation of blast sounds, Isei *et al.*[3] carried out field measurements in hilly lands. They found that the frequency spectrums of excess attenuation were similar, although the geographical features in the propagation paths were different, and proposed the Three-Straight-Line model, in which the excess attenuation versus frequency is described by three straight lines. Figure 1 shows general features of the Three-Straight-Line model. As shown in Fig. 1, the spectrums have been divided into three portions:

Part 1: Frequency range with less excess attenuation

Part 2: Range showing a rapid increase of excess attenuation with an increase of frequency

Part 3: Range showing a slight decrease of excess attenuation with an increase of frequency

On the whole, the excess attenuations increased with the propagation distance. As predominant factors for the excess attenuation in each frequency range, Isei *et al.* pointed out geometrical spreading in Part 1, shielding by the uneven terrain and acoustic impedance of the ground in Part 2, and acoustic impedance and propagation distance (as well as, partly, shielding by the uneven terrain) in Part 3, respectively, based on similarities to noise attenuations over flat and soft ground. In the next section, we compare the model with the data of excess attenuation of blast sounds newly obtained from several field measurements in hilly regions with various terrain features, and examine extension of the model to those longer propagation distances.

3. Field measurements of blast sounds propagating over hilly regions

Outdoor measurements of blast sounds generated by ignition of explosives were made in three hilly regions with different geographical features. The explosives used in the measurements were some amounts of TNT, smokeless powder, water-gel explosives intermediate, and pentolite, which were ignited above the ground surface.

Figure 2 illustrates in cross-section the terrain features between the sound sources and measuring points. Along Path 1, the elevation of the land surface increased gently toward the more distant measuring points, with the ground surface over the propagation distance covered by soil and thick, weedy vegetation. The area around the sound source was the highest in elevation along Path 2, and the elevation decreased toward the measuring points gradually. The ground surface of the hilly regions was covered with shrubs less than 10 m in height along Path 2 and Path 3. The propagation path along Path 3-1 was remarkably undulating, whereas that along Path 3-2 was gently uneven and was along a small river. As shown in Fig. 2, most of the measuring points were not in a direct line of transmission from the sound sources because of uneven terrain features. Low-frequency sound-level meters (RION, NA-17) were placed on tripods at 1.2 m above the ground at the measuring points, and the propagated blast sounds were recorded on DAT recorders (SONY, PC208Ax). Recorded blast sounds were analyzed in 1/3-octave bands by a real-time frequency analyzer (Brüel & Kjær, type 2133).

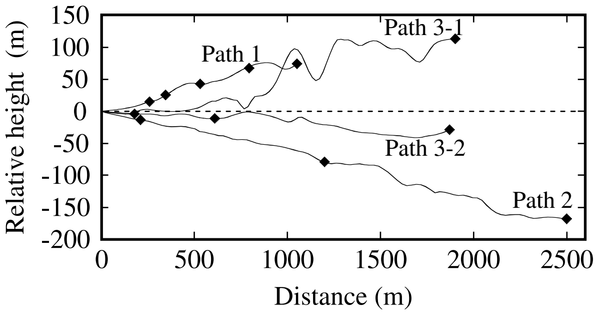

Fig. 2 Uneven terrain in each field measurement. Vertical axis shows elevations relative to those at sound sources. Solid diamonds show measuring points.

4. Results and discussion

4.1 Propagation of blast sounds

Figure 3 shows an example of the sound pressure–time waveforms for 1.5 s of blast sounds obtained from the field measurement along Path 3, and this is the measurement for ignition of 32 kg of TNT. At the measuring point 180 m distant from the blasting point, impulsive increases of sound pressure were clearly observed after ignition of the explosive. The sound pressure decreased rapidly as the propagation distance increased. The waveforms taken at the more distant measuring points were fairly similar to that at 180 m, and the primary peaks of sound pressure remained. From observation of the time waveforms, high-frequency components in the blast sounds that propagated up to the 1903 m measuring point were clearly more attenuated than the other components. We could not find remarkable differences in the overall tendency of the time waveforms even for other measurements in this study.

Figure 4 illustrates the results of the frequency analysis in 1/3-octave bands of the blast sounds shown in Fig. 3. For all the measuring points, the frequency components were primarily below 20 Hz, and frequency bands at around 10 Hz were predominant except for the point at 1903 m. Attenuations at frequencies of more than 50 Hz became larger than those below 50 Hz, when the propagation distance increased. Comparison of the frequency spectrums measured between the 1872 m and 1903 m measuring points shows that the sound pressure levels at 1903 m were generally smaller and attenuated remarkably at frequencies below 20 Hz, even though the difference in propagation distance was small. This may be because of the shielding effect caused by the strong undulation of the terrain along Path 3-1. For all the field measurements, the predominant frequencies of the blast sounds ranged mostly from several Hz to around 30 Hz.

4.2 Comparisons between measured excess attenuation and the Three-Straight-Line model

Excess attenuations relative to the sound pressure levels obtained at the closest measuring point to the source in each measurement were calculated and plotted in Fig. 5. Here, we apply the Three-Straight-Line model shown in Fig. 1 to the results. When the results along Path 1 were compared (see (a), (b), and (c)), the excess attenuations at the various propagation distances were similar even though different explosives were used as the sound sources. The patterns of excess attenuation in the measurements along Path 1 show good agreement with the model, and the attenuation at the 1053 m measuring point especially tended to be almost the same, although the values seemed to be smaller, because the measuring point was slightly shielded by the terrain. With regard to Path 3, the excess attenuations in the case of the water-gel explosives intermediate (see (e)) also agree fairly well with the model except that at the 1872 m point.

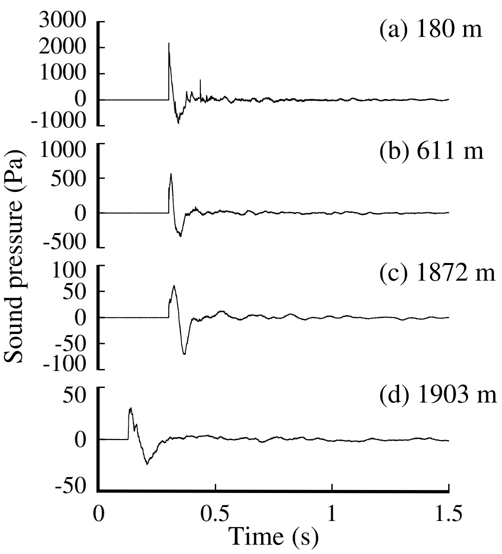

Fig. 3 Comparison of sound pressure–time waveforms measured at points distant (a) 180 m, (b) 611 m, (c)1872 m (Path 3-2) and (d)1903 m (Path 3-1) from sound source (Path 3).

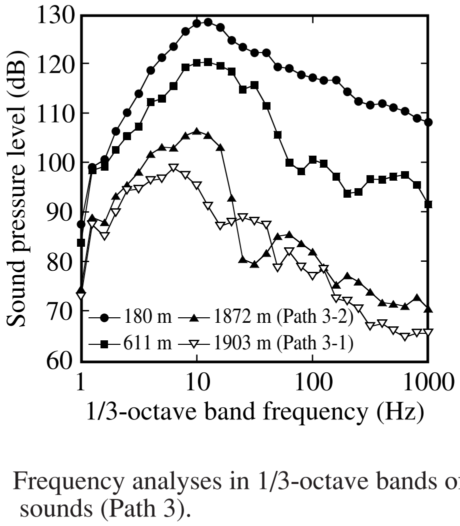

Fig. 4 Frequency analyses in 1/3-octave bands of blast sounds (Path 3).

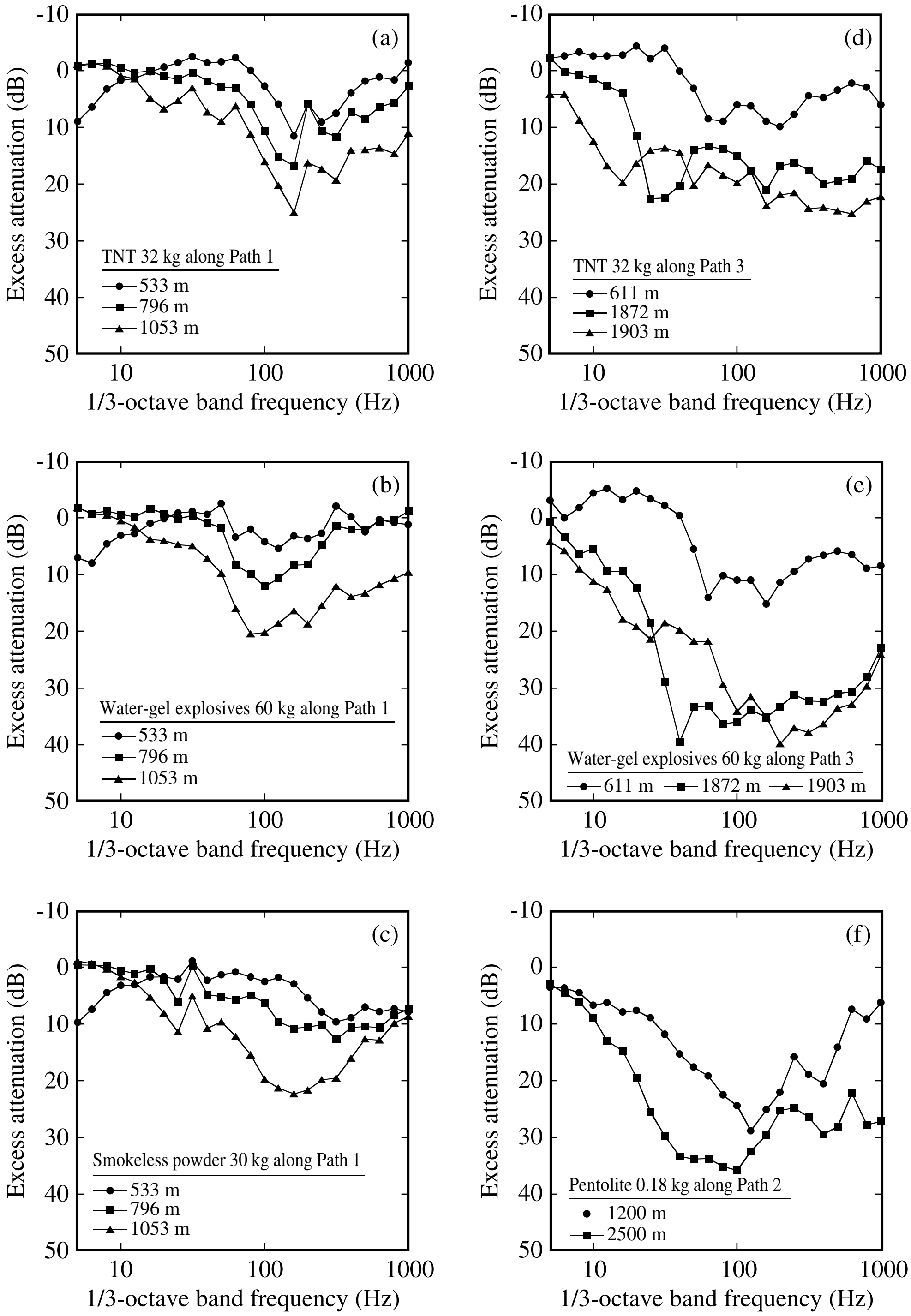

Fig. 5 Excess attenuations of blast sounds.

Because the blast sound propagated to the measuring point along a river in a shallow ravine, it may have been more influenced by reflections off the hill surfaces than by the shielding; consequently, its attenuation trend was different from those at other sites. On the other hand, the agreements in case of the TNT along Path 3 (see (d)) were poor in the high-frequency range at the more distant measuring points. This difference may have been caused by meteorological conditions, because the measurements at relatively shorter distances agree well with the Three-Straight-Line model. With regard to frequency ranges for transition from Part 1 to Part 2 in the Three-Straight-Line model (see Fig. 1), the ranges indicated in (d), (e), and (f) seemed to shift to lower frequencies. We suppose that the contributions of the acoustic surface and acoustic ground waves in the blast sounds decreased owing to the longer range propagation.

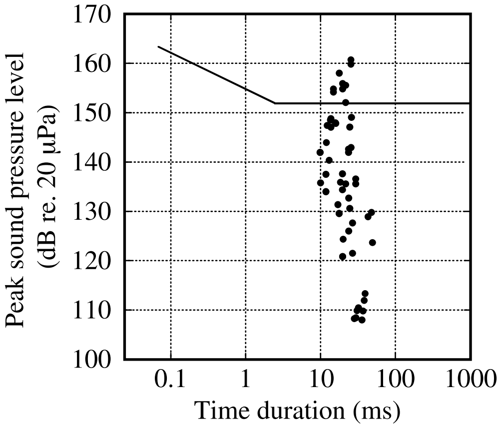

Fig. 6 Comparison between a hearing-protective criterion governing impulsive sound in workplace (solid line) and peak sound pressure levels of blast sounds.

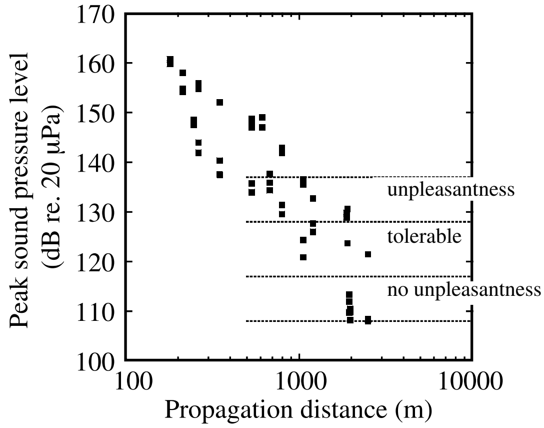

Fig. 7 Comparison between peak sound pressure levels of blast sounds in propagation distance and psychological reactions to sonic booms.

4.3 Environmental impacts due to blast sounds from occupational and psychological points of view

In order to estimate the environmental impacts due to the blast sounds after long-range propagation, we applied two indices, that for preventing hearing loss caused by impulsive noises in the workplace and that for the psychological reaction of human beings exposed to sonic booms.

Figure 6 plots the relationship between peak sound pressure levels and time duration of the impulsive part of the observed blast sounds. From the sound pressure–time waveforms of the blast sounds, we can apply hearing-protective criterion governing impulsive noise in the workplace[11] shown on the figure by a solid line. Peak sound pressure levels of the blast sounds ranged from 110 to 160 dB, and most of the sounds were below the levels specified by the hearing-protective criterion except those measured close to the sound sources. Figure 7 is a plot of the attenuation of the peak sound pressure levels in distance. As compared with the psychological reactions to sonic booms, the blast sounds measured at the measuring points more than 1 km away were mostly classified into the categories “tolerable” or “no unpleasantness.” Physical phenomena corresponding to these categories are described as “distant explosions or thunder” and “blast sounds which can be barely heard,” respectively. As a result, we estimate that psychological complaints are likely to occur rarely at areas more than 1 km away from the sound sources.

4.4 Relationship between predictions by the Three-Straight-Line model and estimation of environmental impacts

Figure 8 compares the peak sound pressure levels with the excess attenuations at predominant frequencies of the blast sounds observed at each measuring point in the field measurements. As the figure shows, a linear correlation exists. From this relationship, we may be able to estimate environmental impacts based on the peak sound pressure levels, as shown in Figs. 6 and 7, through prediction of the excess attenuations at the measuring points. Therefore, the Three-Straight-Line model can be used effectively to calculate the excess attenuations, because the shielding effect of topography cannot be estimated in the same way as that for noise barriers[13].

On the other hand, the Three-Straight-Line model is still qualitative, and it is difficult for the model to quantitatively show relationships between excess attenuation and parameters such as degree of terrain undulation or propagation distance. In order to improve the Three-Straight-Line model quantitatively and then to use it to appropriately evaluate the environmental impacts from acoustical points of view, further investigation is needed.

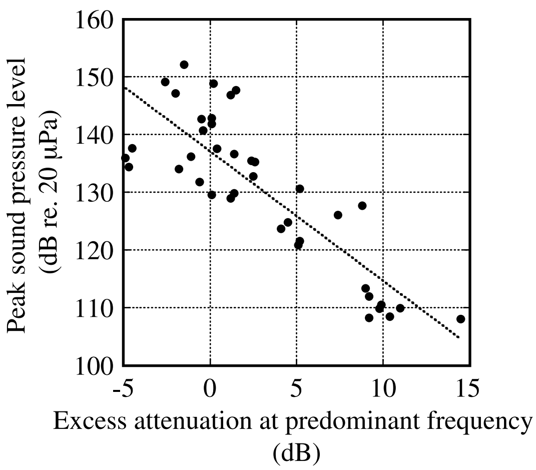

Fig. 8 Comparison between peak sound pressure levels and excess attenuations at predominant frequencies of blast sounds. A dotted line is obtained by a linear approximation.

5. Conclusion

We pointed out that the Three-Straight-Line model mostly agrees with the excess attenuations of blast sounds propagated up to about 2.5 km in varied terrain in hilly regions, while transitions from Part 1 to Part 2 tended to appear at lower frequencies due to the longer range propagation. From the results, we considered that the Three-Straight-Line model could be extended to the propagation distance.

Environmental impacts to the surrounding area of the blast sounds may be small, based on the field measurements, since we showed that psychological complaints and noise-induced hearing impairments would occur only rarely at distances of a few kilometers from the source. We also noted that the excess attenuations of the blast sounds correlated linearly with the peak sound pressure levels, and showed that it is possible to use the Three-Straight-Line model to estimate environmental impacts to the surrounding area from acoustical points of view.

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丘陵地を超えて伝搬する爆発音の超過減衰と職業安全及び心理的反応の観点からの評価

今泉博之*†，高橋保盛*，井清武弘**，黒田英司***，
中山良男***，堀口貞茲***，吉田正典***

【要旨】

本研究の目的は,屋外実験によって得られた火薬類の爆発音の実測データを用い,丘陵地域を伝搬する爆発音の超過減衰量に対して提案された"3直線モデル(Three-Straight-Line model)"の適用性を検討するとともに,衝撃騒音に対して聴力保護の立場から定められた許容基準及びソニックブームによる心理的反応との比較から,その爆発音が及ぼす周辺環境への影響を考察することである。

爆発音が様々な地形に沿って2.5 km程度伝搬する間に計測された超過減衰量は,3直線モデルによって推計された値と概ね一致した。その際,超過減衰が明確に現れる周波数は伝搬距離が増加すると低周波数へ移行する傾向があった。実測結果の一部は数100 Hzより高い周波数帯でモデルよりも大きな減衰量を示したが,これは伝搬距離の増加と空気の音響吸収によることが示唆された。以上の検討結果から，3直線モデルが従来以上の長距離を伝搬した爆発音に対しても適用可能であることが明らかになった。

計測された爆発音のピーク音圧レベルは110 dBから160 dBの範囲であり,爆点近傍における爆発音を除く大部分が,それらの持続時間との関係から衝撃騒音に対する許容基準値を下回った。また,ソニックブームの聴取に対する心理的反応と比較すると,爆点から1 km以上離れた計測点におけるピーク音圧レベルは"我慢できる"あるいは"不快感なし"に分類された。つまり,屋外実験で計測された爆発音は,職業安全や心理的反応の観点から爆点から1 km以上離れた周辺環境に対してわずかに影響を及ぼす程度であると考えられた。

*(独)産業技術総合研究所 地圏資源環境研究部門　〒305-8569　つくば市小野川16-1
†corresponding author: hiroyuki.imaizumi@aist.go.jp

**ベトナム炭鉱ガス安全管理センター　Phuong Trung Vuong, Uong Bi Town, Quang Ninh, VIETNAM

***(独)産業技術総合研究所 爆発安全研究センター　〒305-8565　つくば市東1-1-1