Research paper

Blast mitigation by a full-scale concrete wall

Tomotaka Homae†, Tomoharu Matsumura, Kunihiko Wakabayashi, and Yoshio Nakayama

Research Core for Explosion Safety, National Institute of Advanced Industrial Science and Technology (AIST), Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, JAPAN
† Corresponding address: to-homae@aist.go.jp

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Abstract

Blast mitigation by a full-scale concrete wall was evaluated. Cylindrically shaped TNT, weight of 80 kg was put on a wooden table, height of 0.6 or 0.8 m. Two kinds of concrete walls, height of 2.5 m from the ground level and width of 4 m were prepared. The distance from the TNT to the wall was 2 m. The blast pressure was measured at a total of 12 points, at four distances in three directions. The directions were 20°, 45°, and 90°, where 0° was defined as the vertical from the TNT to the wall plane. The scaled distance from the TNT was 2, 4, 8, and 16 $m \cdot kg^{-1/3}$. The peak pressure at direction of 20° and scaled distance of 4 $m \cdot kg^{-1/3}$ was remarkably mitigated. The peak pressure at direction of 20° and scaled distance of 8 and 16 $m \cdot kg^{-1/3}$ was almost the same as that without the wall. The peak pressure at direction of 45° and 90° was lower and higher, respectively, regardless of the distance. The impulse was mitigated at the point of direction of 45° and 4 $m \cdot kg^{-1/3}$. However, the obvious mitigation was not observed at all other points. Precise data, including typical blast wave profiles and the blast parameters, are presented in the text.

Keywords: Blast wave, Mitigation, Concrete, Wall.

1. Introduction

A wall is often used to protect people and valuables from the blast wave caused by an unexpected explosion. The mitigation of blast waves by walls has been extensively studied. However, the blast mitigation data from full-scale experiments is seldom published in Japan. Sudo reported the mitigation effect of a full-scale wall [1]. However, the precise result and the blast data are not described in the report. Although Mizushima also reported the mitigation effect of a full-scale wall [2], the pressure measurement in the report did not have time resolution.

In this paper, the mitigation of a blast wave by a full-scale concrete wall is discussed. Precise data, including the blast wave profiles and the blast parameters, are presented. These data should be useful to examine the technical standards of walls at fireworks mills.

2. Experimental Procedure

2.1 Explosives and Ignition

In this paper, the results of three experiments are described. The standard blast parameters without the concrete wall were obtained in experiment # 1. The mitigated blast parameters by a conventional concrete wall were obtained in experiment # 2. The mitigated blast parameters by a new high-strength concrete wall were obtained in experiment # 3.

The weight and density of the explosives are summarized in Table 1. Cylindrically shaped TNT of approximately 80 kg was used as a main explosive. The diameter was 394-399 mm, and the height was 410 mm. Pentolite, weight of 2 % of TNT, was used as a booster. Two exploding-bridgewire detonators (RISI RP-501) were

Table 1 The weight and density of explosives.

No.	TNT Weight (kg)	TNT Density ($kg \cdot m^{-3}$)	Booster Pentolite weight (kg)	Pentolite density ($kg \cdot m^{-3}$)	Total weight (kg)
# 1	78.3	1,580	1,563	1,600	79.9
# 2	78.7	1,580	1,563	1,600	80.3
# 3	78.4	1,580	1,564	1,600	80.0

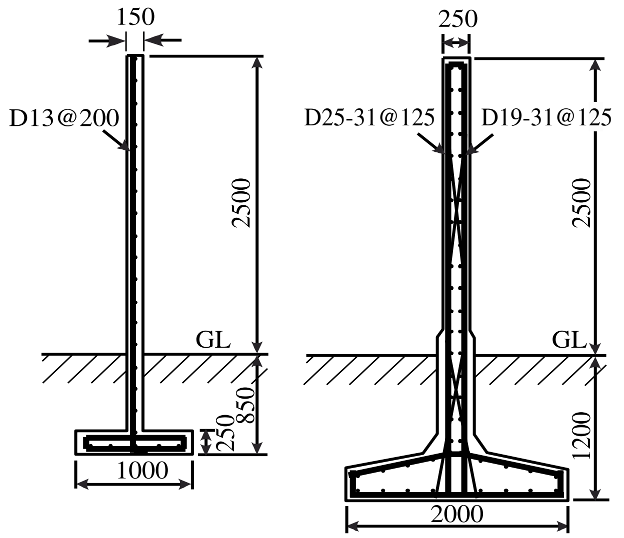


Fig. 1 Two kinds of concrete walls. (a) conventional concrete wall for experiment #2, and (b) high-strength concrete wall for experiment #3.

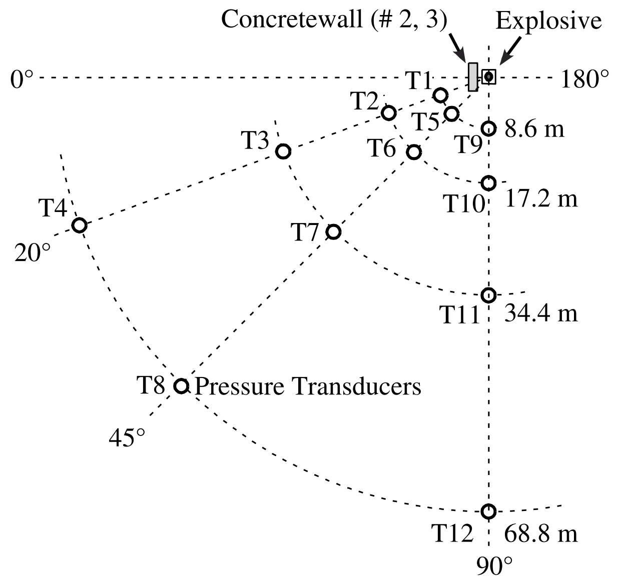


Fig. 2 Setup of blast pressure measurement on the experiment field. T1-T12 correspond to the transducer number.

used for each experiment. The explosive was put on a wooden table, height of 600 mm (# 1) or 800 mm (# 2 and # 3), and ignited.

2.2 Concrete wall

Two full-scale concrete walls were prepared for the experiment. The dimensions of the walls are shown in Fig. 1. One of the walls, referred to as the conventional wall, was similar to walls generally and conventionally constructed. Another wall, referred to as the high-strength concrete wall, aimed at the prevention of falling down. The conventional wall was 2500 mm in height above ground level, 4000 mm in width, and 150 mm in thickness. The high-strength wall had the same height and width as the conventional wall, but the thickness was 250 mm. The distance from the TNT exterior to the wall surface was 2000 mm.

2.3 Blast Measurement

The distribution of the pressure transducers is represented in Fig. 2. The blast pressure was measured at a total of 12 points, at four distances in three directions. The directions measured were counterclockwise in angles of θ = 20°, 45°, and 90°, where 0° was defined as a vertical from the TNT to the wall plane. The distance from the TNT was 8.6 m, 17.2 m , 34.4 m, and 68.8 m, corresponded to the scaled distance K of 2, 4, 8, and 16 $\mathrm{m \cdot kg^{-1/3}}$, respectively. Hereinafter, the unit $\mathrm{m \cdot kg^{-1/3}}$ is omitted, and the scaled distance is represented as K = 2, for example. To avoid direct hits of the concrete fragments to the transducers, the transducers were not placed at θ = 0°. Piezoelectric pressure transducers (PCB 102M256) were used to measure the blast pressure. The transducers were set with a flush-diaphragm parallel to the ground. The height of the transducer was 1 m from ground level. The outputs of the transducers were recorded using digital data recorders (Labortechnik Tasler LTT184, sampling rate of 1.04 MHz and vertical resolution of 16 bit in this study) through the amplifiers (H-TECH).

3. Results and Discussion

After the explosion, the concrete walls were destroyed as follows. The conventional concrete wall (# 2) fell down completely. A conic hole, diameter of 2.5 m and depth of 0.34 m, appeared at ground zero. Almost all of the concrete was exfoliated at the middle-height portion of the wall. The concrete remained at the upper portion. Many cracks were observed on the underground foundation portion. Conversely, the high-strength concrete wall (# 3) inclined to the other side of the explosion of 5 degrees, but did not fall down. A conic hole, diameter of 2.5-2.6 m and depth of 0.21 m, appeared at ground zero. Cracks were observed on the both sides of the wall.

Almost all of the blast wave profile was clearly obtained by the transducers. However, the transducers placed at K = 2 showed an unusual rapid decay for the blast pressure and suspicious oscillation after the arrival of the blast wave. These data were regarded as incorrect and eliminated from further analysis except for the arrival time. According to pictures from a high speed camera, such transducers were exposed to an explosion flame directly. The heat of the flame affected the transducers and thus caused these anomalous wave forms.

The start of the pressure increment of the obtained pressure wave form was regarded as the arrival time of the blast wave. The obtained wave profiles were fitted using a spline function. The peak pressure, the duration of the positive phase, and the positive impulse were determined based on the fitted curve. The duration of the positive phase and the positive impulse are referred to as duration and impulse, respectively, hereinafter. The obtained blast parameters are summarized in Table 2.

Table 2 Obtained blast parameters.

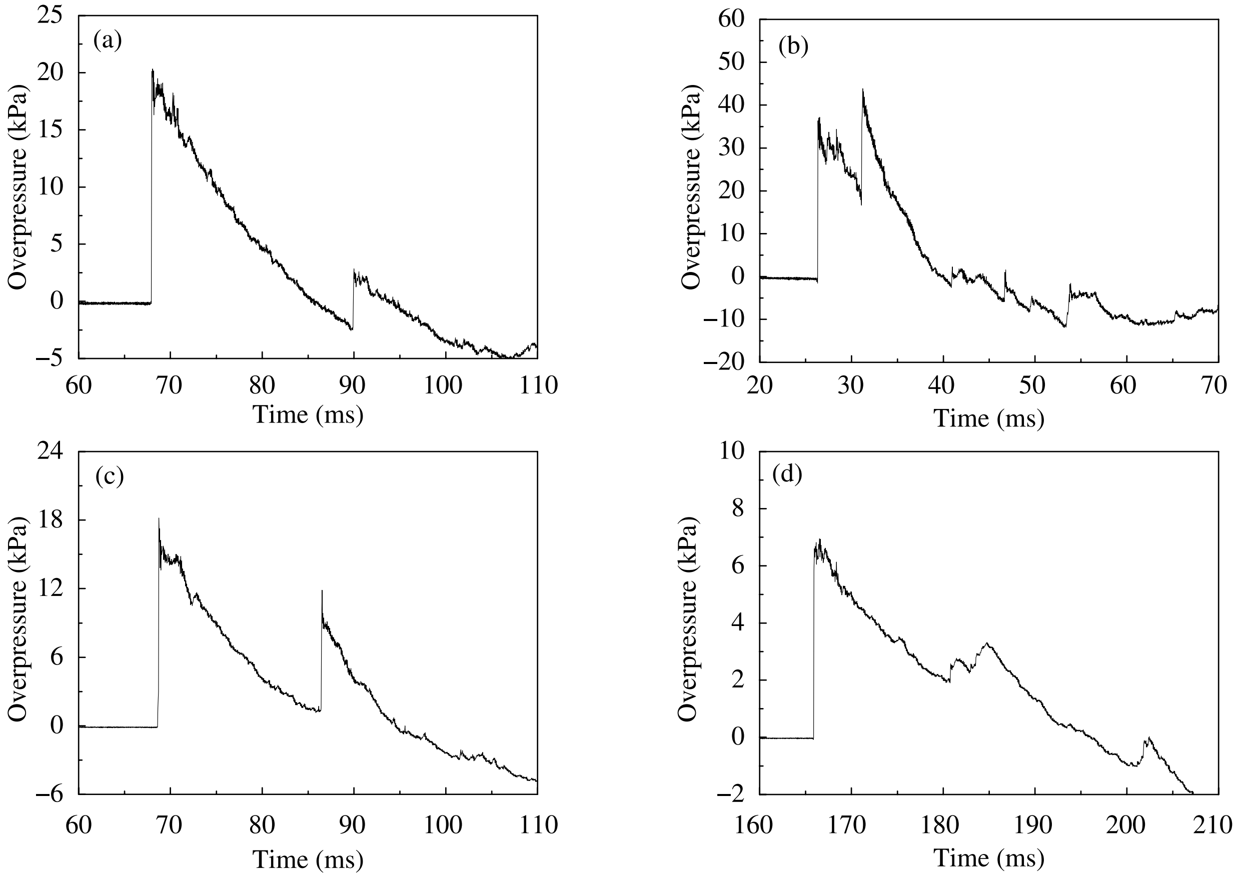
Experiment No.	Transducer No.	Distance from TNT (m)	Scaled distance ($m \cdot kg^{-1/3}$)	Peak pressure (kPa)	Time of arrival (ms)	Duration (ms)	Impulse (Pa · s)
# 1	T1	8.12	1.89	—	5.63	—	—
	T2	16.77	3.89	63.7	22.41	12.36	284.0
	T3	34.07	7.91	19.1	67.72	17.94	153.6
	T4	68.57	15.92	7.7	165.87	22.24	78.7
	T5	8.27	1.92	—	5.77	—	—
	T6	16.91	3.93	77.3	22.73	11.76	292.3
	T7	34.22	7.95	19.6	67.90	17.81	156.5
	T8	68.67	15.95	8.6	165.91	22.26	80.7
	T9	8.61	2.00	—	6.22	—	—
	T10	17.18	3.99	67.5	23.10	12.98	288.5
	T11	34.49	8.01	19.0	68.00	17.73	151.6
	T12	68.94	16.01	7.3	165.08	22.73	77.9
# 2	T1	8.16	1.89	144.9	7.27	9.60	360.4
	T2	16.78	3.89	41.5	26.35	13.74	273.9
	T3	34.10	7.91	20.2	72.36	20.74	160.2
	T4	68.60	15.90	8.3	168.98	23.57	81.2
	T5	8.31	1.93	—	5.19	—	—
	T6	16.89	3.92	61.8	22.57	9.13	215.7
	T7	34.24	7.94	16.6	68.67	26.04	161.8
	T8	68.67	15.92	6.5	165.99	30.24	84.7
	T9	8.62	2.00	—	6.16	—	—
	T10	17.16	3.98	76.7	22.16	11.41	312.2
	T11	34.51	8.00	22.1	66.23	16.31	153.0
	T12	68.92	15.98	7.8	162.48	21.33	77.5
# 3	T1	8.16	1.89	124.1	8.38	10.97	368.0
	T2	16.78	3.89	36.7	27.47	15.43	269.5
	T3	34.10	7.92	19.1	73.66	20.40	152.1
	T4	68.60	15.92	7.8	170.61	23.42	80.4
	T5	8.31	1.93	—	5.98	—	—
	T6	16.89	3.92	59.5	23.69	9.47	212.2
	T7	34.24	7.95	15.8	69.46	26.17	157.9
	T8	68.67	15.94	6.5	167.05	29.64	83.5
	T9	8.62	2.00	—	6.12	—	—
	T10	17.16	3.98	71.4	22.34	10.85	306.8
	T11	34.51	8.01	21.4	66.74	16.67	151.4
	T12	68.92	16.00	7.7	163.36	20.93	75.8

"-" implies that the wave profile is not clear enough to determine the value precisely.

Typical blast-wave profiles of the surface burst were obtained in experiment #1. The profiles did not depend on the direction, as the condition was almost isotropic. A typical wave profile is shown in Fig. 3 (a). The secondary shock was observed at approximately 90 ms. The re-expansion following the expansion and the contraction of the explosion products generated this secondary shock. The concrete wall also generated a second pressure peak as described later. They can be distinguished by the duration of the negative phase. The average shock velocity, the peak pressure, the scaled impulse, and the duration of experiment # 1 are represented in Figs. 4-7. The mitigation effect of the wall was discussed based on comparison of the results of experiment # 2 and 3 with that of # 1, later in this paper.

3.1 Characteristics of the mitigated blast wave

The wave profiles of experiment # 2 and # 3 showed the same characteristics. The examples of these profiles are shown in Figs. 3 (b)-(d). The most characteristic profile was obtained at $\theta = 20°$ and $K = 4$. The profiles were affected by the presence of the wall, and the peak of these profiles split into two peaks. The second peak showed larger pressure than the first peak (Fig. 3 (b)). The peak pressure was determined using this larger value. The obtained profiles at $\theta = 20°$, $K = 8$ and 16 were similar to that without the walls. All of the profiles obtained at $\theta = 45°$ were affected by the wall. At $K = 8$, the second peak was larger than half of the first peak (Fig. 3 (c)). At $K = 16$, a bump was observed on the decay process of the first shock (Fig. 3 (d)). The profiles at $\theta = 90°$ were similar to those without the wall, but the secondary shock was larger than those without the wall, regardless of the distance.



(a) Typical wave profile of the surface burst of experiment # 1 at $\theta = 90°$ and $K = 8$.
The secondary shock was observed at approximately 90 ms. This secondary shock should be distinguished from the second pressure peak, observed in (b)-(d).
(b) Wave profile at $\theta = 20°$ and $K = 4$ of experiment # 2. Second peak is larger than the first one.
(c) Wave profile at $\theta = 45°$ and $K = 8$ of experiment # 2. Second peak is quite large.
(d) Wave profile at $\theta = 45°$ and $K = 16$ of experiment # 2. A bump on the decay process of the first shock is observed.

Fig. 3 Obtained blast waveforms.

3.2 Arrival time and shock velocity affected by the wall

The arrival time at $\theta = 20°$ and $K = 2$ was 7.27-8.38 ms behind the wall or 5.63 ms without the wall (Table 2). The distance between the explosive and the transducer at $K = 2$ was 8.6 m, while the distance via the top of the wall was 9.4 m and that via the side of the wall was 9.7 m. As the difference of the arrival time is larger than the difference of the distance, the revolving of the blast wave behind the wall may take some time.

The average shock velocity between the two neighbor transducers was determined and is represented in Fig. 4. Assuming that the time of explosion was 0, the average velocity between the explosive and $K = 2$ was also determined. The shock velocity reduced with the distance in general. The average shock velocity at $\theta = 20°$ and $K < 4$ is remarkably slow. This can be due to the revolving behind the wall described above. At the other points, including the points of $\theta = 20°$ and $K > 4$, the effect of the wall to the shock velocity was not observed, and the shock velocity depended only on the distance from the explosive. This tendency is different compared with other blast parameters described later.

3.3 Peak pressure mitigation

The obtained peak pressure is represented in Fig. 5. The peak pressure at $\theta = 20°$ and $K = 4$ was remarkably mitigated. The obvious mitigation of the peak pressure at $\theta = 20°$, $K = 8$ and 16 was not observed. The peak pressure decreased at $\theta = 45°$ and increased at $\theta = 90°$, respectively, regardless of the distance. These results suggest that the effect of the wall can reach to the far point. The peak pressure of experiment # 2 was up to 10 % larger than that of experiment # 3 for the same point. As the time for the wall to fall down is much longer than that for the blast wave passing through, the effect of falling down to the peak pressure should not be dominant. The rigidity of the wall, which affects the reflection, and the shape of the wall, in which factors such as the thickness are different between two walls, can affect the difference of the peak pressure.

3.4 Impulse mitigation

The obtained scaled impulse, which is the impulse divided by the cubic root of the TNT weight, is represented in Fig. 6. The impulse at $\theta = 45°$ and $K = 4$ was mitigated. However, obvious mitigation of the impulse was not

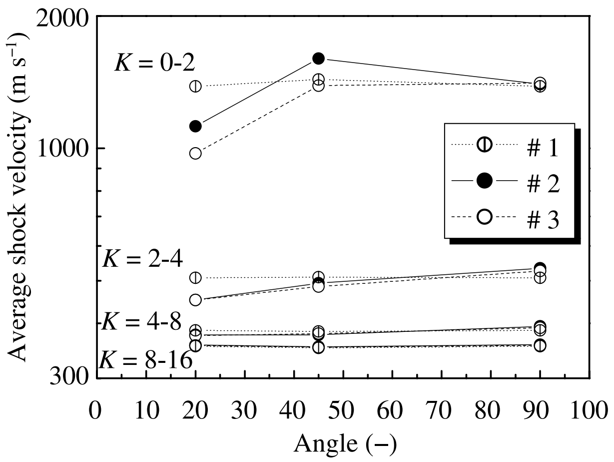


Fig. 4 Average shock velocity.

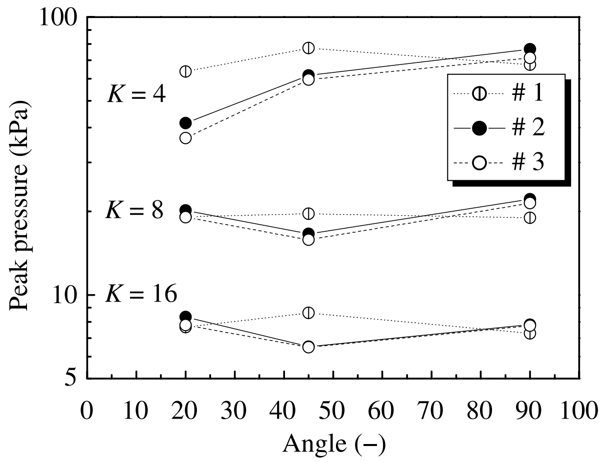


Fig. 5 Peak pressure.

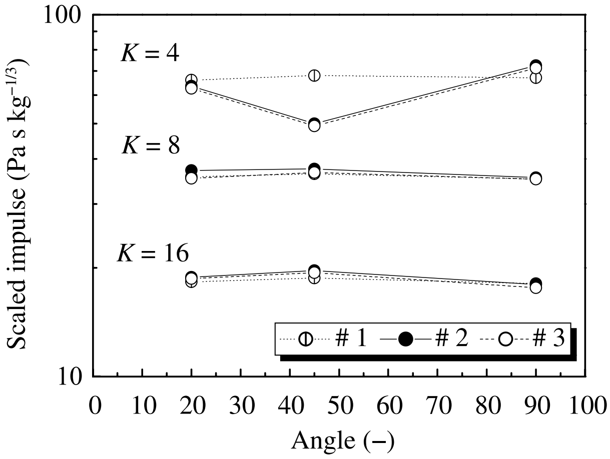


Fig. 6 Scaled impulse.

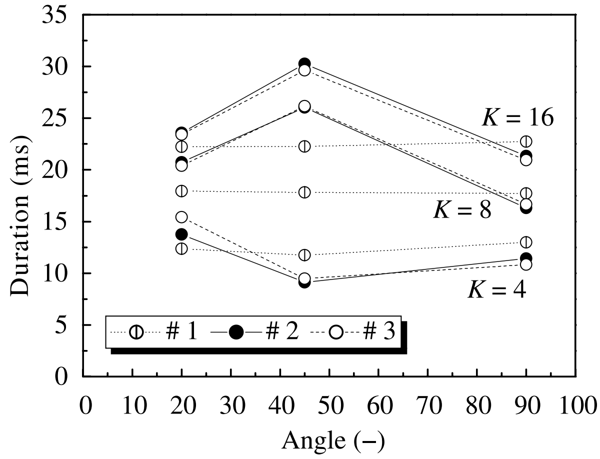


Fig. 7 Duration of blast waves.

observed at all other points. The difference of the wall type did not remarkably affect the impulse, while the difference affected the peak pressure as described above.

3.5 Duration

The peak pressure and the impulse showed different mitigation tendency, because the duration was different, depending on the direction. The obtained duration is shown in Fig. 7. The duration at $\theta = 45°$, $K = 8$ and 16 was longer than that at $\theta = 90°$, in reverse of the peak pressure. Hence, the impulse, which was integral for the pressure waveform on the pressure-time plane, corresponded at these two angles. Naturally, the duration of experiment # 1, without the wall, did not depend on the direction, as shown in Fig. 7.

4. Conclusion

Blast mitigation by a full-scale concrete wall was evaluated. Two kinds of walls with differing strength were examined. The results obtained are as follows:

1) The peak pressure at $\theta = 20°$ and $K = 4$ was remarkably mitigated. The peak pressure at $\theta = 20°$, $K = 8$ and 16 was almost the same as that without the wall. The peak pressure at $\theta = 45°$ and $\theta = 90°$ was lower and higher, respectively, regardless of the distance.
2) The impulse was mitigated at $\theta = 45°$ and $K = 4$. However, obvious mitigation was not observed at all other points.
3) The difference of wall type varied the peak pressure up to 10 %. In general, the stronger wall mitigated the blast wave more effectively. The effect to the impulse was small compared to the peak pressure.

These results should be useful to examine the technical standards of walls at fireworks mills.

References

1) S. Sudo, J. the Industrial Explosives Society (Sci. Tech. Energetic Materials), 23, 160 (1962), in Japanese.
2) Y. Mizushima, J. the Industrial Explosives Society (Sci. Tech. Energetic Materials), 31, 361 (1970).

実大スケール防爆壁による爆風影響低減

保前友高[†]，松村知治，若林邦彦，中山良男

80 kg の TNT を地上高さ 0.6-0.8 m の木製台上に置き、2 種類の防爆壁（地上高さ 2.5 m、幅 4 m）から 2 m 離して点火し、3 方向（20 度 , 45 度 , 90 度）の各 4 点（換算距離 2, 4, 8, 16 m・kg$^{-1/3}$）で爆風圧計測を行った。ピーク圧力は、爆点から見て防爆壁の裏側に当たる 20 度方向の換算距離 4 m･kg$^{-1/3}$ では、大幅に低減され、換算距離 8, 16 m･kg$^{-1/3}$ では、防爆壁がない場合と変わらなかった。45 度方向では、距離によらず全般に低め、90 度方向では、全般に高めであった。インパルスに関しては、換算距離 4 m･kg$^{-1/3}$ の 45 度方向の地点では、低減が確認されたが、それ以外の地点では、防爆壁がない場合とほとんど変わらなかった。

独立行政法人　産業技術総合研究所　爆発安全研究コア　〒305-8565　茨城県つくば市東1-1-1　中央第５

[†]Corresponding address: to-homae@aist.go.jp