Research paper

Large-scale explosion experiment of a model underground magazine

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Abstract

We conducted a large-scale explosion experiment to assess blast wave characteristics of a model underground magazine. The magazine tunnel and storage chamber were modeled by a cylindrical steel pipe with one end closed by a reinforced panel. The static overpressures of the blast were measured by piezo-electric pressure sensors set up in three locations at four azimuth angles. TNT charges of 1.2 kg, 6 kg and 30 kg in mass were ignited by a pentolite booster and EBW detonators. Free field explosion of TNT charges weighing 1 kg and 30 kg were conducted to obtain standard blast data. It was found that the peak overpressures decreased with the azimuth angle at the same scaled distance, and the peak overpressures at 60° were higher than that of the free field blast data. The directionality of blast waves decreased at a far distance, but appreciable directionality remained at a far distance. The results of the present study agreed well with our previous studies (1 kg and 0.6 g TNT). The results clearly demonstrated the applicability of the scaling law on the propagation of blast waves around a model underground magazine.

Keywords: Underground magazine, Blast wave, Large-scale, Safety distance

1. Introduction

An underground magazine with a storage chamber and an exit is called a shotgun type, and this is the simplest structure. From the safety point of view, related parameters that should be considered for blast characteristics around underground magazine are numerous. For instance, peak pressure depends on magazine chamber size (diameter, length, and height), tunnel size, and loading density (ratio of the stored mass of the explosive to the volume of the magazine chamber), etc. Therefore, many researchers use metallic models which are not destroyed easily due to the explosion of explosive [1)~7)]. Skjeltorp, et al. proposed empirical equations in which the attenuation index of peak overpressure versus scaled distance was constant for all azimuth angles [1)]. The assumption is used in the safety standard of DDESB [8), 9)]. We have investigated blast propagation around small scale model magazines to clarify the directionality of the blast wave and attenuation index of peak overpressure versus scaled distance [5)~7)]. Our conclusion was that the attenuation index was not constant, and it varies depending on the azimuth angles. In this report, an experiment on the condition of increasing the amount of the explosive mass was conducted, and the similarity of the blast wave characteristics was studied.

The purpose of the present study is to obtain the blast wave parameters by a large scale model magazine and make a comparison with small scale results to confirm the similarity law between the small scale model results and the present experiment results.

2. Experiments

Table 1 shows explosive used in the test. Experiment No.1 represents the ground surface explosion of TNT charges. TNT charges weighing 1 kg and 30 kg were conducted to obtain standard blast data. Experiment No.2 is a model underground magazine test. The shape of the TNT charges in Experiment No.1 and No.2 are almost right cylinders except for No.2-3. The amount of booster charge is approximately 2 % wt. of each TNT charge. TNT charges were ignited by a pentolite (TNT50 / PETN50 wt.%) booster, a double-hold detonating fuse and exploding bridge-wire (EBW) detonators (RISI-501) with RDX based mixture explosive (0.4 g). The length of the detonating fuse is one meter for No.1 and approximately 10 m for No.2.

Figure 1 shows a model underground magazine used in test No.2. The magazine tunnel and storage chamber were

Table 1 Explosive

Exp. No.	Name	Mass (kg)	Outer diameter (mm)	Length (mm)	Density ($kg \cdot m^{-3}$)
1-1	TNT	1.191	99.7	100.2	1,550
	Pentolite	0.024	27.0	27.2	1,630
1-2	TNT	29.97	293.2	293.6	1,550
	Pentolite	0.638	79.2	79.9	1,620
2-1	TNT	1.191	99.8	100.5	1,550
	Pentolite	0.024	27.2	27.0	1,620
2-2	TNT	6.038	171.8	172.7	1,540
	Pentolite	0.13	46.8	47.0	1,620
2-3	TNT	30.18	232.9	466.3	1,550
	Pentolite	0.638	79.2	80.6	1,620

Pentolite: TNT50 / PETN50 wt.%

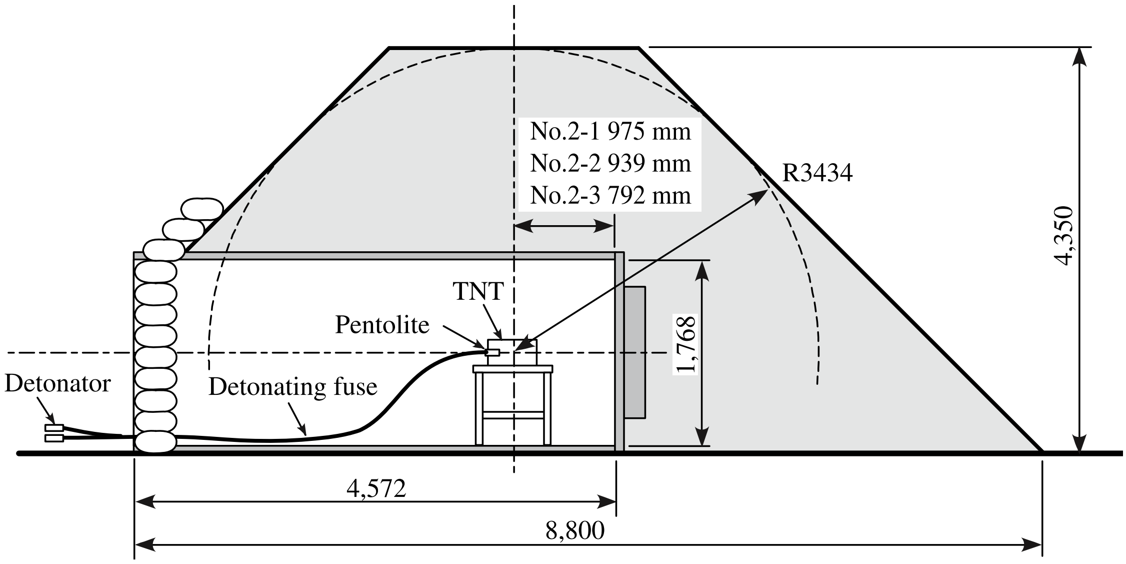

Fig. 1 Schematic cross sectional view of the model magazine.

modeled by a cylindrical steel pipe with one end closed by reinforced panels. The inner diameter, inner length, and maximum wall thickness were 1768 mm, 4572 mm, and 32 mm, respectively. The chamber was covered with soil, the maximum height was 4350 mm from ground level, and its width at bottom was approximately 10 m. The explosive was placed at the center of the model magazine as shown in the Fig. 2.

The static overpressures of the blast were measured by piezo-electric pressure sensors (PCB H102A07 and H102A12). The distances for Exp. No.1 were 15, 25, 38 and 51 m from the explosive center. The azimuth angles from the exit of the model were 0, 60, 120 and 160 °, and the distances from the exit of the model to the sensors were 25, 38 and 51 m.

The blast wave pressures were recorded by using a digital waveform recorder (Gage Applied Inc., Gage 1610, 16 Bit, 10 MS / s).

3. Results and discussion

3.1 High speed photography results

Figure 2 shows the results of high-speed photography taken at 1000 fps. It was found that the expansion of explosion gas is not a spherical shape. A rapid expansion was observed in the right direction. The results may suggest a directionality of propagation of the blast wave. It was found that the chamber was deformed partially but was not destroyed by the explosion of 30 kg of TNT. The confirmation of the model magazine seemed to be complete.

3.2 Static overpressure time records

Figure 3 shows the pressure-time traces at ≈ 38 m from the exit (at azimuth angles of 0°, 60°, 120°, and 160°) generated by the detonation of a TNT charge with a mass of 6.038 kg. It was found that the larger the azimuth angle, the lower the peak static overpressure and scaled impulse, and the slower the time-of-arrival. It was found that the peak overpressure of the front side (= 0° and 60 °) is greater than that of the reverse side (= 120° and 160°). The experimental results of peak static overpressure are higher than that of surface explosion of TNT at small azimuth angles.

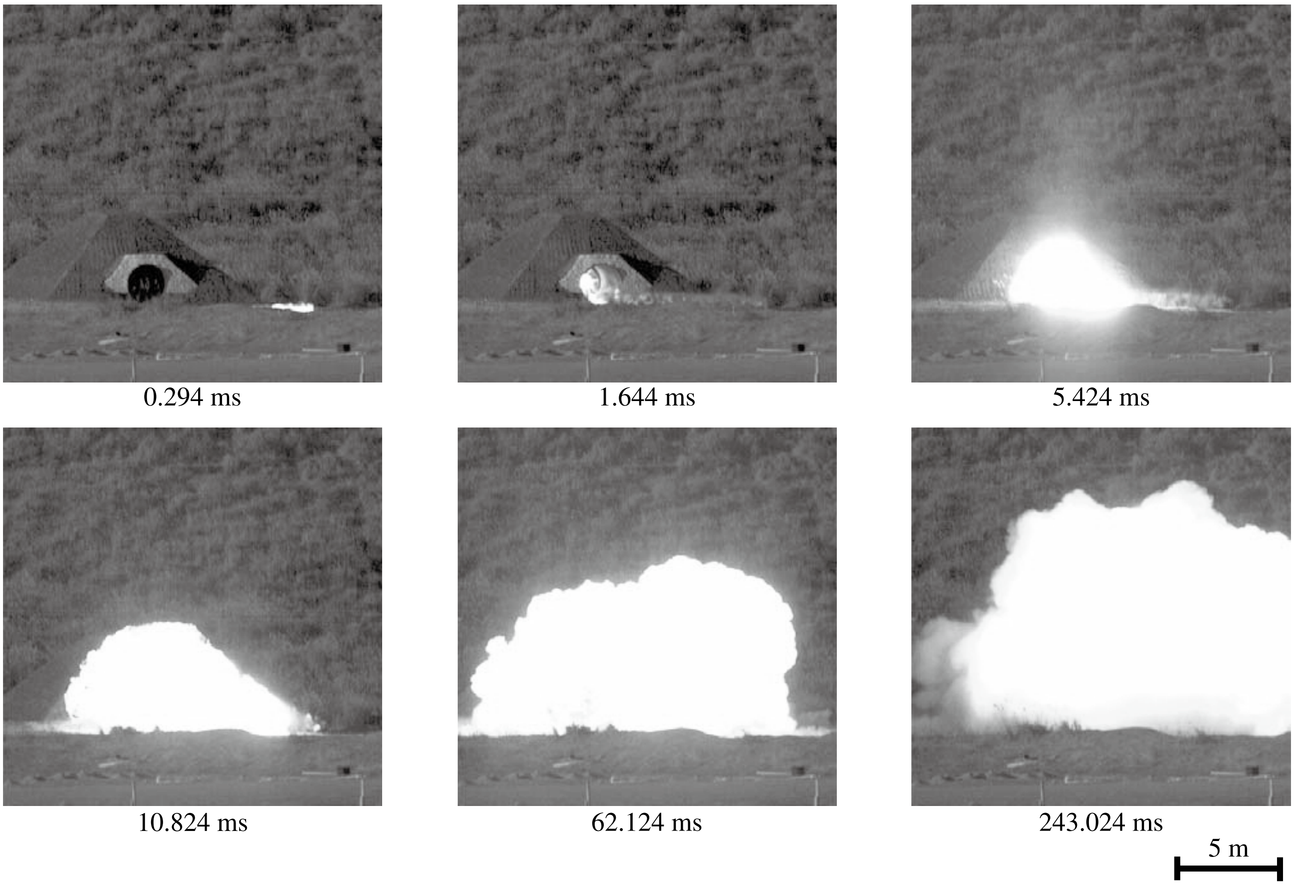

Fig. 2 The result of high-speed photograph for explosion of TNT 30 kg in model underground magazine.

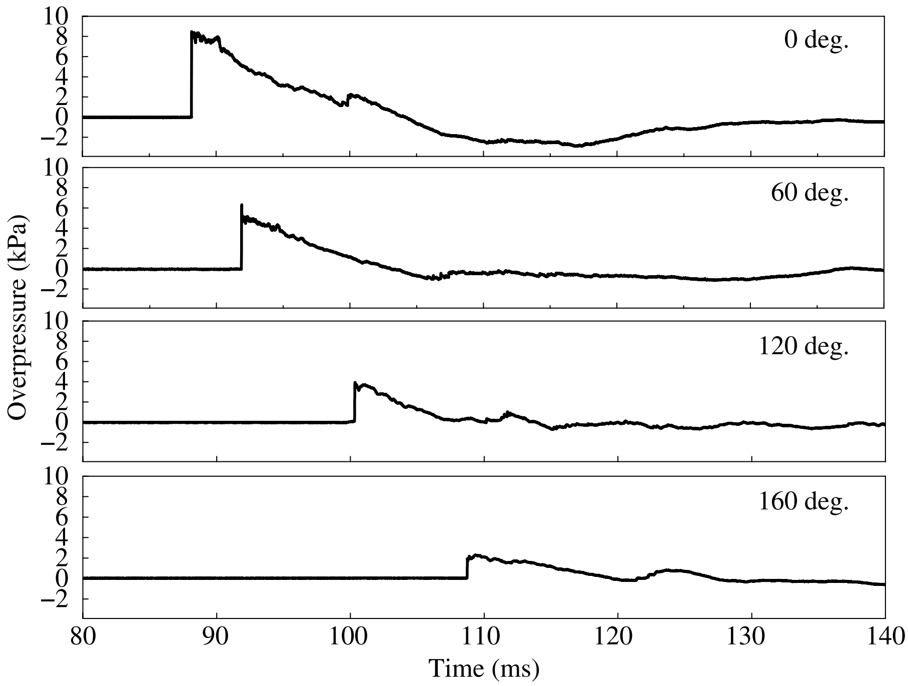

Fig. 3 Pressure-time records of static overpressure for four azimuth angles. The explosive is a TNT 6.038 kg.

3.3 Scaled distance versus blast parameters

The time-histories were interpolated by smooth cubic natural spline functions to obtain four characteristic blast parameters: peak static overpressure, time-of-arrival, duration of positive pressure, and the positive pressure impulse (the time-integral of the overpressure during the positive pressure phase). The reference data from the surface burst of TNT by MITI87 [10] and the free-air explosion by Baker [11] are plotted in the figures.

Figures 4 to 7 show the experimental results of peak overpressure, scaled impulse, scaled time-of-arrival, and

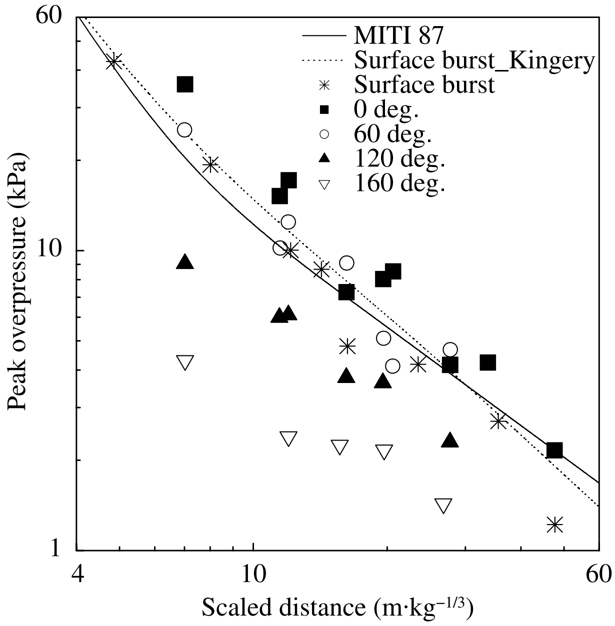

Fig. 4 Peak static overpressure vs. scaled distance.

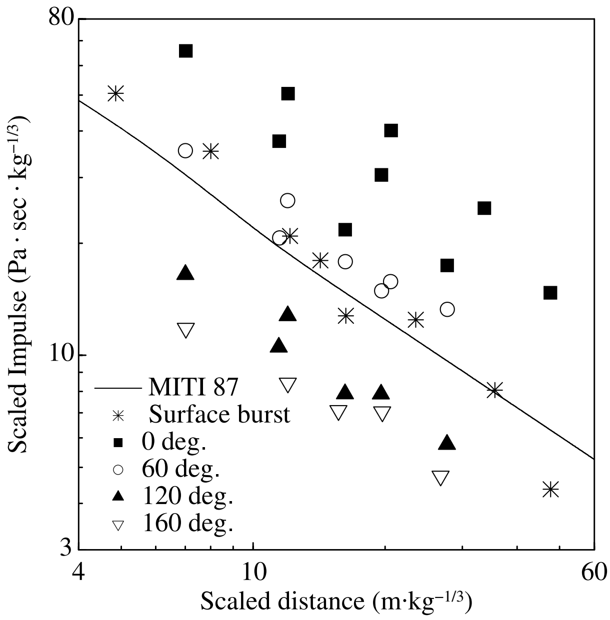

Fig. 5 Scaled positive impulse vs. scaled distance.

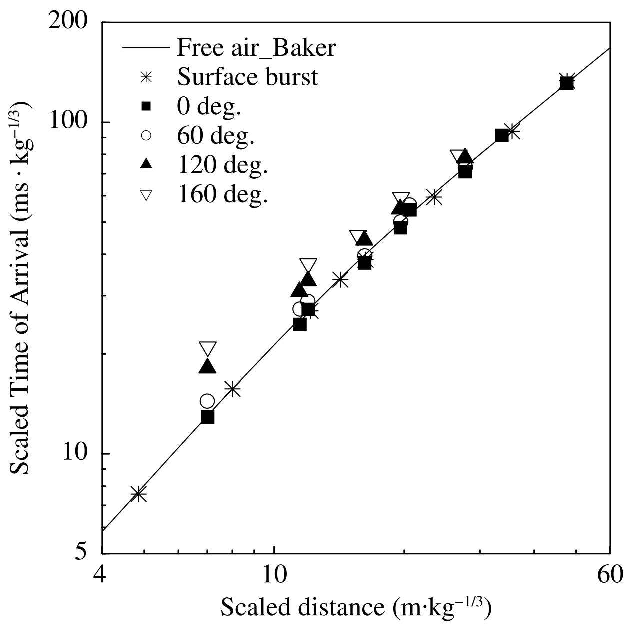

Fig. 6 Scaled time-of-arrival vs. scaled distance.

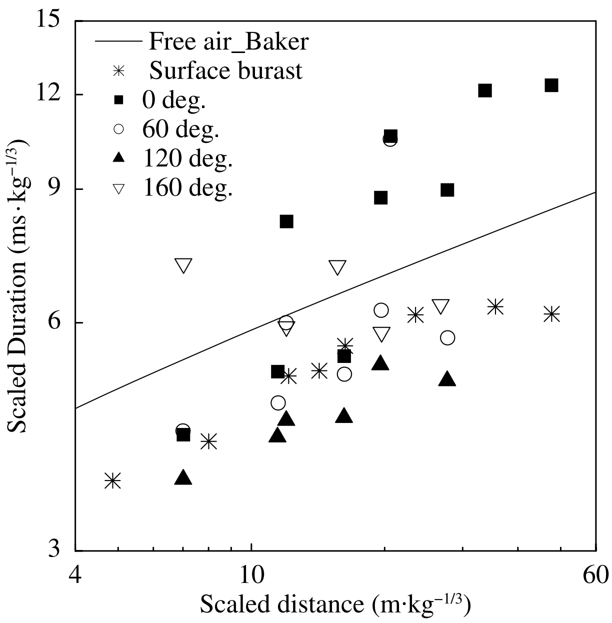

Fig. 7 Scaled duration vs. scaled distance.

scaled duration with respect to the scaled distance. It was found that Experiment No.1 results agreed with the surface burst of TNT by MITI87. So, it was confirmed that the present experiment shows a good validity. Figure 4 shows that the peak overpressure decreases significantly as the azimuth angle increases. The peak overpressures of 0° are more than four times than the one of 120°. Another point to note is that the peak overpressures at azimuth angles of 0° and 60° are approximately equal or larger than that of the surface burst. This means that the safety distance at azimuth angles of 0° and 60° are approximately equal or larger than that of a surface burst.

3.4 The decay of peak static overpressure

Distance attenuation characteristics were investigated from the data obtained at approximately between 20 m and 50 m. The empirical formula below (1) was used to evaluate the attenuation of the peak static overpressure as a function of scaled distance.

$$\Delta p = k(R / Q^{1/3})^{n} \tag{1}$$

where R is the distance (in meters) from the exit, Q is the charge mass (in kg), Δp (in Pa) is the peak static overpressure, k is the attenuation constant, and n is the attenuation index. Table 2 shows the values of the charge mass, the azimuth angle, k, and n. The attenuation index for the present results at azimuth angles of θ = 0°, 60°, 120°, and 160° became n = –1.532, –1.287, –0.904, and –0.655, respectively. The experimental results by Skjeltorp et al. [1], Millington [2], Nakahara et al. [3] and Nakayama et al. [5), 6)] are included in Table 2. Skjeltorp reported that n = –1.35 for azimuth angles of 0° to 180°. However, as the azimuth

Table 2 The observed results of the attenuation constant k and the attenuation index n.

Method	Explosive	Charge mass Q (kg)	Azimuth angle θ (deg.)	Constant k (Pa)	Index n (−)	Scaled distance ($m \cdot kg^{-1/3}$)
Present	TNT	6.04 and 30.18	0	8.45 (E+02)	−1.532	7-28
			60	3.40 (E+02)	−1.287	
			120	6.24 (E+01)	−0.904	
			160	1.67 (E+01)	−0.655	
Nakayama	TNT	0.2, 0.5 and 1.0	0	5.76 (E+03)	−1.54	5-30
			90	1.57 (E+03)	−1.31	
			180	0.544 (E+03)	−1.16	
Nakayama Model No.1	Detonator #6 and #0	0.172 (E-03) and 0.626 (E-03)	0	2.3 (E+02)	−1.26	5-55
			90	1.0 (E+02)	−1.19	
			180	0.13 (E+02)	−0.806	
Skejeltorp	TNT	0.095-0.152	0, 30, 60, 90, 120, 150, and 180	—	−1.35	1.3-67
Millington	RDX/TNT = 60 / 40 wt %	0.163	0, 45 and 90	—	−4/3	1-10
Nakahara	TNT	9.49-343	0	1.67 (E+06)	−1.7	0.7-5

angle increases, the absolute value of the attenuation index decreases for the present study, and may decrease to a constant value of $n = -1$ at a far distance (which corresponds to the value for a spherically decaying sound wave). One of the present authors reported the same trend [5), 6)]. It may be reasonable to conclude that attenuation index is a function of azimuth angle.

3.5 Directionality of blast waves

The pressure ratio of peak static overpressure as a function of azimuth angle is used to investigate the directionality of blast waves. Pressure ratio is expressed by the following equation.

$$\Delta p(\theta) / \Delta p(\theta = 0°) = 1 / [1 + (\theta / \mathrm{a})^2] \qquad (2)$$

where parameter a is a constant defined from experimental results. Skjeltorp reported that a = 56° [1)]. If θ equals a, then the right hand side equals a half. Therefore, the parameter denotes the directionality of the blast wave propagating outside of the tunnel exit. If the parameter is small, the directionality of blast is high. Equation (2) is designated by broken line in Fig. 8. Several results were shown in the same figure. The symbol ○ denotes the results from Millington by using a steel pipe model (RDX / TNT / 60 / 40 w t%, and mass is 0.163 kg) [2)]. The symbol □ denotes the results from Nakahara et. al. by using a reinforced steel concrete model (the cross sectional view is square at the bottom and dome shaped at the ceiling) (TNT 9.49 kg to 343 kg) [3)] . The black symbols represent data developed by one of the present authors. The symbols ● , ▲ , and ▼ are steel model-1, model-2, and model-3, respectively (cross sectional views are square) (0.6 g TNT equivalent mass) [5)].

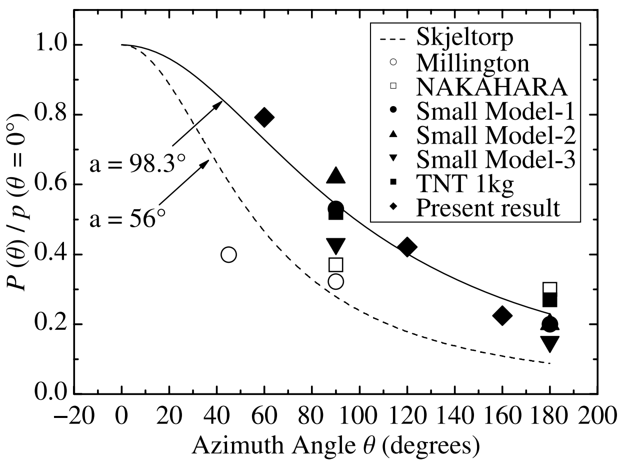

Fig. 8 Pressure ratio of peak static overpressure as a function of azimuth angle at scaled distance of 16 $m \cdot kg^{-1/3}$.

The symbol ■ denotes a steel model (the cross sectional view is square) (TNT mass 0.25 ~ 1 kg) [6)]. The symbol ◆ denotes the present results. All the values are estimated at a scaled distance of 16 $m \cdot kg^{-1/3}$. The small steel model-1 and the large steel model are similar in shape such as the ratio of cross sectional area of the tunnel (A_t) to that of the chamber (A_c), A_t / A_c, and the ratio of tunnel length to chamber length (L_t / L_c). Therefore the result of the small steel model-1 (the symbol is ●) and the large steel model (the symbol is ■) agrees quite well from the Fig. 8. The solid line in the Fig. 8 denotes the interpolated results of the small steel model-1, the large steel model, and the present data (the symbol is ◆) by Equation (2). It is found that the present study agrees well with our previous studies (1kg and 0.6 g TNT) from Fig. 8. The results clearly demonstrated the applicability of the scaling law on the propagation of blast waves around a model underground magazine.

The results by Skjeltorp are different from our results. This means that the blast wave has high directionality. The reason for this may be attributed to factors such as loading density (kg·m^{-3}) of explosives in a magazine, ratio of a cross sectional area of the tunnel (A_t) to the cross sectional area of the chamber (A_c), A_t / A_c, and length to the diameter ratio of tunnel (L_t / D_t). It is reported that the results by Skjeltorp have a high correlation with the results from the shock tube data with one end open. The blast wave emerging from a long pipe tends to have a highly directional character, and the pressure ratio at 180° is smaller. Skjeltorp used a steel magazine with a large L_t / D_t = 86, and gave the minimum pressure ratios as shown in Fig. 8.

4. Conclusions

We conducted a large-scale explosion experiment to assess blast wave characteristics of a model underground magazine. It was found that the larger the azimuth angle, the lower the peak static overpressure and scaled impulse, and the slower the time-of-arrival. The peak overpressures at azimuth angles of 0° and 60° are approximately equal or larger than that of the surface burst. In other words, the shock waves propagated forward and the weak pressure waves propagated backward. The directionality of the blast wave was weaker at greater distances. The present study agrees well with our previous studies (1 kg and 0.6 g TNT). The results clearly demonstrated the applicability of the scaling law on the propagation of blast waves around a model underground magazine.

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モデル地中式火薬庫の大規模爆発実験

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モデル地中式火薬庫周囲の爆風伝播特性を調査するために、大規模の野外爆発実験を実施した。火薬庫のトンネル部と薬室部は円筒形の鋼管でモデル化され、薬室部奥は補強された蓋が溶接された構造である。爆風計測のため、一方向に３点で４方向にピエゾ圧力計を設置し、爆風の静水過圧を計測した。ペントライト伝爆薬と線爆発型特殊雷管を使用して、薬量1.2～30 kgのTNT爆薬を起爆した。基準爆風圧データ収集のため、薬量1 kgと30 kgのTNT爆薬の地表爆発も実施した。その結果、換算距離が同一の場合、ピーク過圧は方位角が増加すると大きく減衰することが確認された。また方位角60度以内のピーク過圧は、地表爆発の結果より高めであることが明らかになった。以上よりモデル地中式火薬庫周囲の爆風の指向性は近距離では顕著であるが、距離とともに指向性は低下すること、実験した範囲内では、遠方でも若干の指向性は存在することを確認した。さらに、本結果は、著者らのこれまでの一連の小規模モデル実験（TNT薬量1 kg と0.6 g）の結果とも一致する傾向であることが確認された。これより、モデル地中式火薬庫周囲の爆風伝播に関して相似則が成立することが明らかになった。

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