Research paper

# Small-scale explosion experiment of an underground magazine model

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## Abstract

Small-scale experiments were carried out using a model of an underground magazine in an explosion chamber. The propagation characteristics of the blast wave of the exterior of the magazine model resulting from an explosion within the magazine model were investigated. The main points of interest are the angle variation and the spatial attenuation of the blast wave overpressures. The experimental results show that the blast wave overpressures diminished with the distance from the exit of the magazine model and with an increasing azimuth angle measured from the centerline of the exit. Interestingly, the lowest blast overpressure did not appear at the rear of the magazine model. These results are useful for the design of safer storage facilities for explosives.

***Keywords*** : blast wave, peak overpressure, impulse, small-scale experiment, magazine, angle variation

## 1. Introduction

In recent years, due to the housing situation and the high rate of industrial development, the number of instances in which high energetic materials (explosives) are stored near residential districts has been increasing. If an accidental explosion was to occur in such an area, the blast wave resulting from the explosion could cause serious damage to structures as well as loss of human life. Thus, the design of storage facilities requires a higher degree of safety.

Explosives are sometimes stored in an underground magazine such as a tunnel in a mountain. If the mountain were large enough, it would not be destroyed by an explosion, and the blast wave would exit from the entrance to the magazine and propagate through the surrounding area. The propagation characteristics of a blast wave produced by an explosion inside a magazine have been investigated experimentally by many researchers[1-3]. However, little research has been conducted concerning the relation between the attenuation of blast wave overpressure and direction (azimuth angle). Full-scale experiments carried out in the field would be ideal, but they would be costly and involve a high degree of risk. In addition, it is difficult to study blast wave propagation in detail because of restrictions on the location and frequency of experiments. This situation, therefore, requires a small-scale experiment.

Our previous small-scale study[4] has investigated the propagation characteristics of a blast wave resulting from the explosion of 1.0 g of material in an explosion chamber. However, that study verified only the blast wave pressure generated by the detonation at the ground surface. In this study, small-scale experiments were carried out using a solid magazine model that was based on an underground magazine. The attenuation and propagation characteristics of blast wave pressure were investigated in detail.

## 2. Experiments

Figure 1 shows the solid magazine model, which was based on an underground magazine. The solid magazine model comprises a steel plate, a cylindrical steel vessel and a steel cover. The steel plate was welded to the cylindrical vessel and the steel cover.

The explosives used in this experiment were 1.0 g of PETN/SR (PETN with silicon rubber as a binder[4] in a ratio of 70 : 30 by weight). The explosives were ignited by small-sized electric detonators (Showa Kinzoku Kogyo Co. Ltd.), which include 0.1 g of lead azide. The explosive charge of the detonator was less than 10% of the mass of the PETN/SR. During these experiments, we confirmed

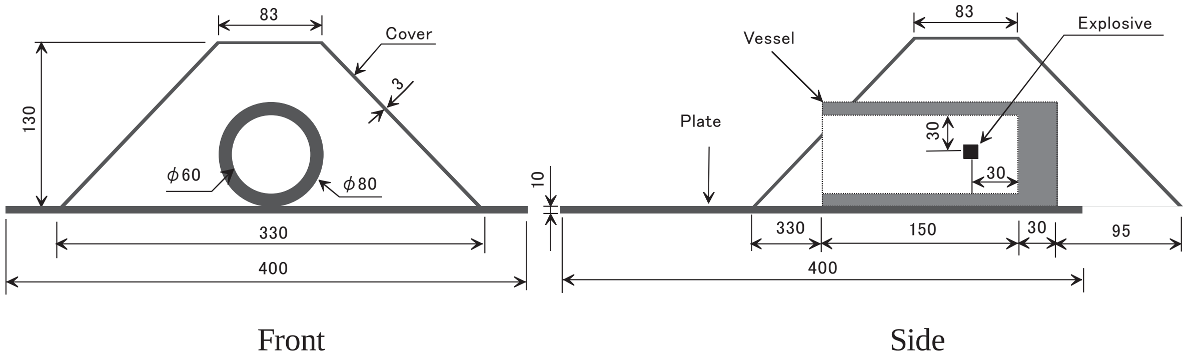


**Fig. 1** Magazine model (unit : mm).

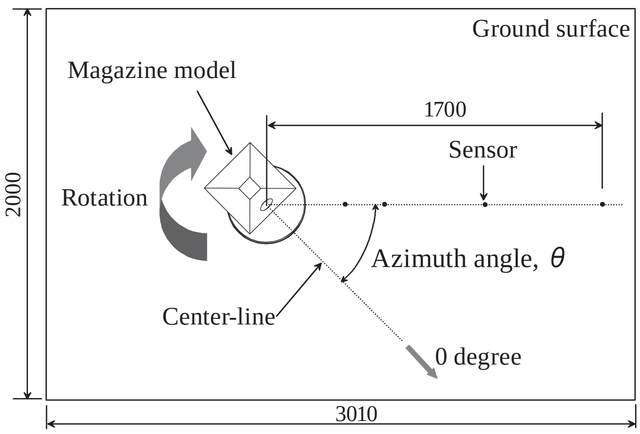


**Fig. 2** Experimental setup for blast overpressure measurement (unit : mm).

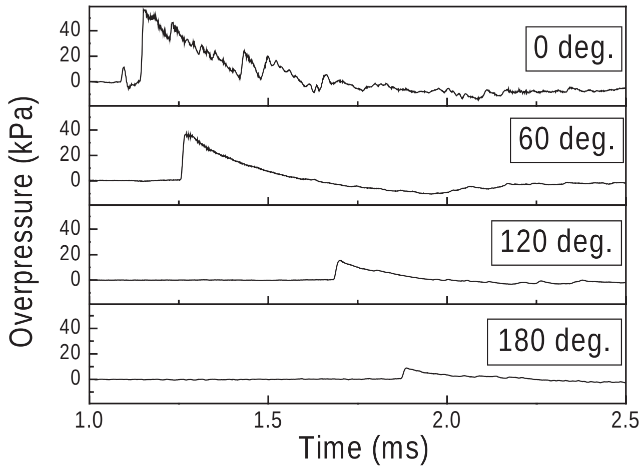


**Fig. 3** Blast wave histories at 0,60, 120 and 180 degrees and 0.6 m (= 6.7 m·kg$^{-1/3}$).

that the magazine model did not suffer any deformation due to the explosion.

Figure 2 shows the experimental setup. A steel plate (2000 × 3010 × 10 mm) was used to represent the ground surface. The solid magazine model was fixed to the ground surface with a damping rubber element (chloroprene) to minimize the vibration generated by the explosion. The solid magazine model was rotated in order to measure the blast static overpressure at 10 degrees intervals in the azimuth angle ($\theta$), which is the direction of the sensors measured from the extended centerline of the magazine (see Fig. 2).

The blast wave overpressure propagating on the ground surface was measured by four piezoelectric sensors (PCB piezotronics Inc., HM 102A), which were located 0.4, 0.6, 1.1 and 1.7 m from the exit of the model. For none of the sensors were in direct contact with the ground surface, damping rubber elements were used to minimize the effect of the vibration of the steel plate on the pressure sensors.

## 3. Results and discussion

### 3.1 Attenuation characteristics of blast wave

Figure 3 shows blast wave histories in four directions (at azimuth angles of 0°, 60°, 120°, and 180°)at a distance of 0.6 m. At larger azimuth angles, the peak static overpressure was lower and the time of arrival was later. This demonstrates the diffraction of the blast wave from the exit of the magazine model.

Figure 4 shows the experimental results for peak overpressures and scaled impulses at 30 degrees intervals. In Fig. 4, the data for the surface burst were taken from our previous study[4]. The following empirical formula has often been used to evaluate the attenuation of the peak static overpressure or impulse as a function of distance[5].

$$\Delta P, I = k \cdot R^{n} \tag{1}$$

where $R$ is the scaled distance (m·kg$^{-1/3}$) from the exit, $\Delta P$ is the peak static overpressure (Pa), $I$ is the scaled impulse (Pa·s·kg$^{-1/3}$), $k$ is the attenuation constant, and $n$ is the attenuation index. The fitted results are shown in Fig. 4 as straight dotted lines. As the azimuth angle increases, the peak overpressure and the impulse decrease significantly. These parameters (the peak overpressure and the impulse) at the front (0-30 degrees) are greater than the parameters for a surface burst, and at 90-180 degrees these parameters are smaller. This trend is the same at each distance measured (4.4, 6.7, 12.3 and 18.8 m·kg$^{-1/3}$). Thus it is clear that there is some angle variation until 18.8 m·kg$^{-1/3}$.

In Fig. 4, it is easy to find that the direction of 0 degree has the highest blast wave overpressure. However, it is not so easy to determine the direction that has the lowest blast wave overpressure. The lowest peak overpressure and impulse occur around 10 m·kg$^{-1/3}$ between 150 and 180 degrees ; the 180 degree direction does not have the lowest overpressure at all times. Figure 5 shows the blast wave histories to the rear (150, 160, 170 and 180 degrees) at a distance of 1.1 m. It appears that there are two pres-

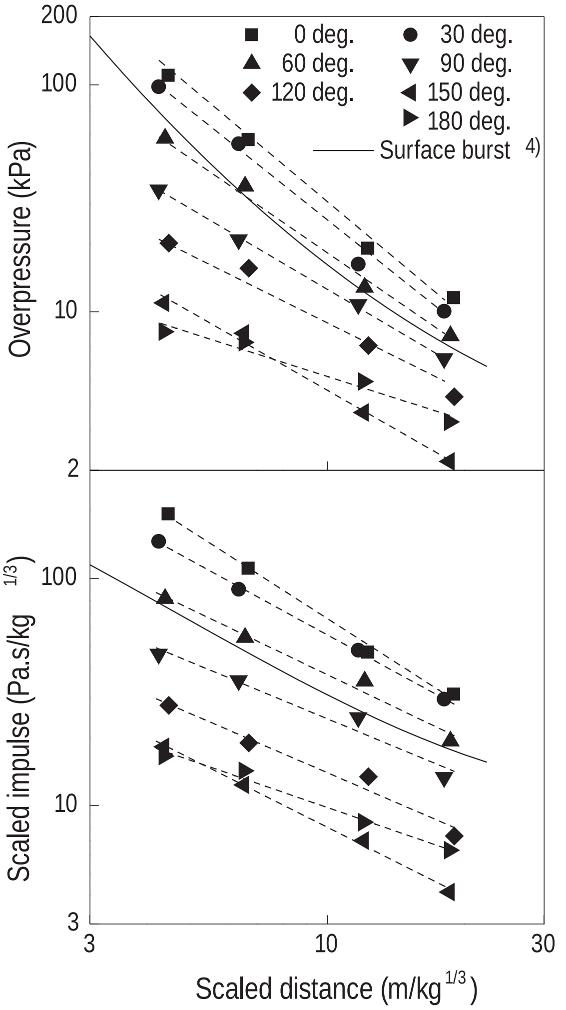


**Fig. 4** Peak overpressure and scaled impulse versus scaled distance.

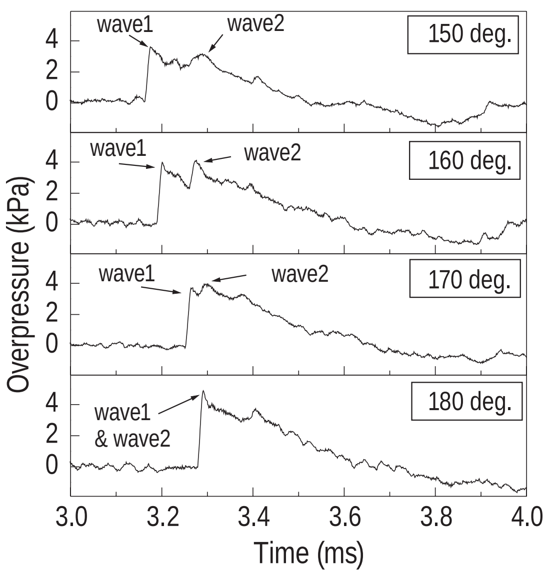


**Fig. 5** Blast wave histories at 150, 160, 170 and 180 degrees and 1.1 m (= 12.3 m·kg$^{-1/3}$).

sure waves. Before the primary wave (wave1) decays to atmospheric pressure, a second wave (wave2) arrives, and then the two waves overlap. The arrival of wave 1 becomes later as the angle increases, whereas wave 2 arrives at almost the same time for any angle. The mechanism for this effect is unclear but we suppose that it is due to blast wave interference at the rear of the model. Further study is needed to understand the mechanism of this phenomenon. However, from all results, it is clear that the direction of 180 degrees does not have the lowest peak overpressure and impulse.

### 3.2 Angle variation of blast wave propagation

Skjeltorp[1] reported the following empirical formula for expressing the angular variation of peak overpressure at a fixed distance from the exit of a tunnel.

$$\frac{P_\theta}{P_{\theta=0^\circ}} = \frac{1}{1+(\theta/\alpha)^\beta} \tag{2}$$

where $P_\theta$ is the peak overpressure at azimuth angle $\theta$, $P_{\theta=0^\circ}$ is the peak overpressure at0degree, and $\alpha$ and $\beta$ are empirical fitting parameters. Skjeltorp[1] found $\beta \approx 2$. However, in this study the parameter fitting the results of our experiment data gives $\beta \approx 2.3$.

Figure 6 shows the pressure ratio $(P_\theta/P_{\theta=0^\circ})$ at 4.4, 6.7, 12.3 and 18.8 m·kg$^{-1/3}$. The curved lines are the fitting results for the data of 0-150 degrees. The formula cannot be used to fit the peak pressures at the rear (160, 170, 180 degrees) because these peak pressures are greater than the peak pressure at 150 degree. It is also found from Fig. 6 that, as the distance increases, the parameter $\alpha$ increases. Although the angle variation of peak overpressures decreases, some angle variation does exist until 1.7 m (18.8 m·kg$^{-1/3}$).

The angle variation of the impulse is also analyzed using the new empirical formula[3] :

$$\frac{I_\theta}{I_{\theta=0^\circ}} = \frac{1}{1+(\theta/\alpha)^\beta} \tag{3}$$

where $I_\theta$ is the impulse at $\theta$ degrees and $I_{\theta=0^\circ}$ is the impulse at0degree. Figure 7 shows that impulse ratio $(I_\theta/I_{\theta=0^\circ})$ at four distances. As the azimuth angle increases from0to 150 degrees, the impulse decreases significantly. This tendency is similar to the result for the peak overpressure. However, the angle variation of the impulse at a given distance is different when it is compared with the angle variation of the peak overpressure. As the distance increases, parameter $\alpha$ varies around the value of 65, which means the angle variation does not vary a lot.

In the United States, the safety distance from a magazine is intimately connected to the peak overpressure[6], not the impulse. Therefore, in order to illustrate the safety distance, Fig. 8 shows the isobars for peak pressures of 8.3 and 15.9 kPa, which are the maximum peak pressure to insure the safety of inhabited building and public traffic routes in the United States. The coordinates of the contours of 8.3 and 15.9 kPa were calculated by approximating the peak overpressure at each azimuth angle using the empirical formula (1). It is clear that the safety distance will be different depending upon direction.

## 4. Conclusions

Small-scale experiments were carried out in an explosion chamber. The propagation and attenuation characteristics of the blast wave resulting from the detonation of

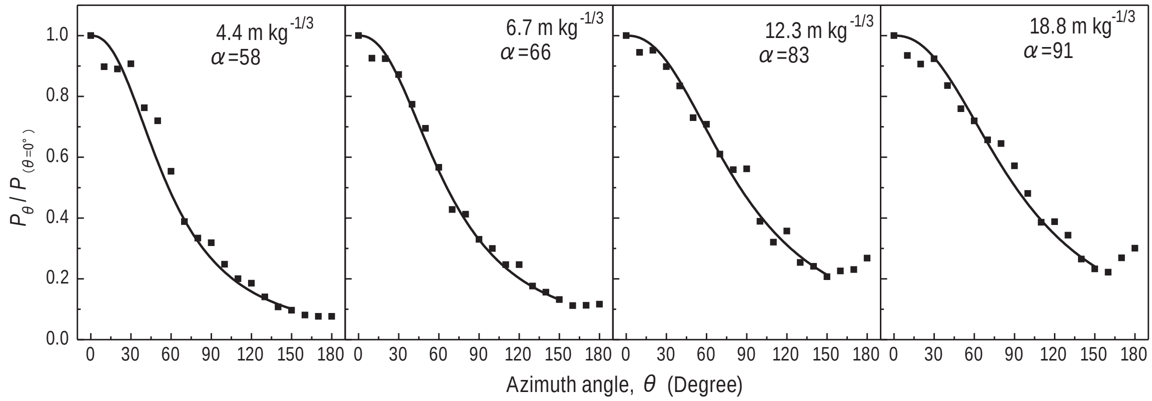


**Fig. 6** Angle variation of peak overpressure at four distances.

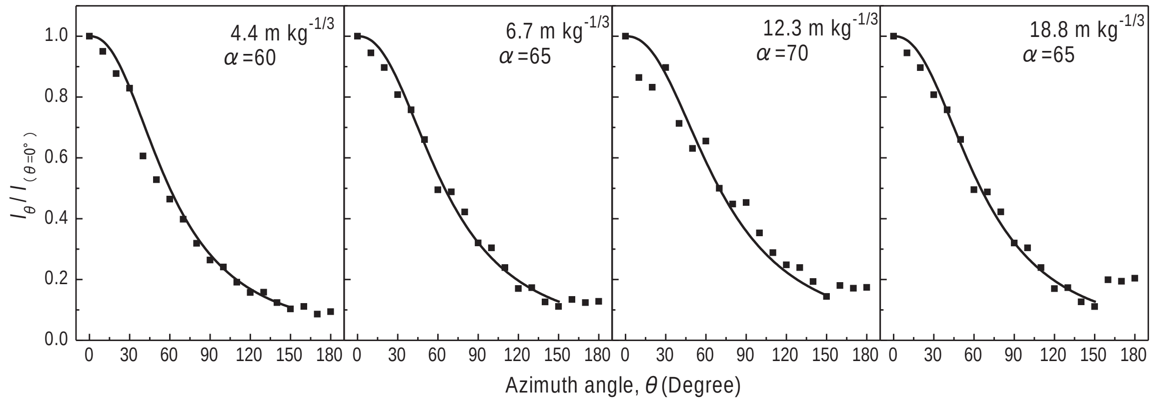


**Fig. 7** Angle variation of impulse at four distances.

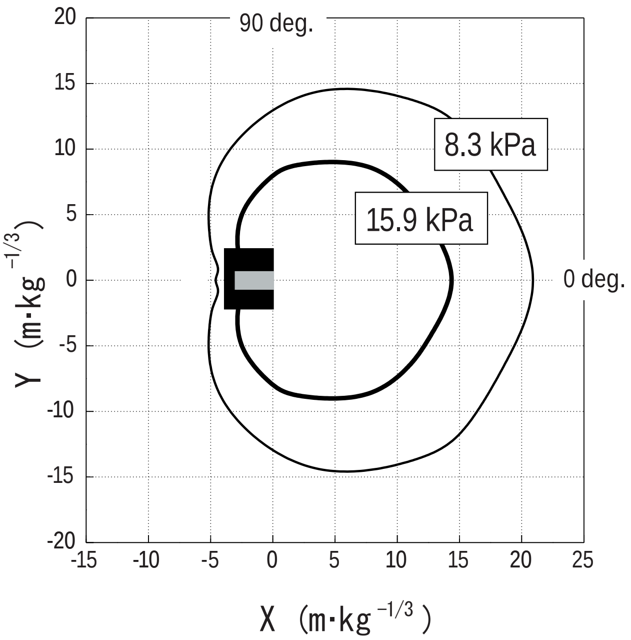


**Fig. 8** Isobars of peak static overpressure.

one gram of explosive inside a model of an underground magazine were investigated out to a distance of 1.7 m. We obtained the following results.

- As the azimuth angle increased, the peak pressures decreased significantly. As the distance increased, the angle variation became smaller, but there was still some angle variation until 18.8 m·kg$^{-1/3}$.
- The impulse decreased as the azimuth angle increased. As the distance increased the angle variation did not vary greatly.
- The lowest value of overpressure did not occur at the rear of the magazine, that is, 180 degree from the exit. The minimum occurred at 150 or 160 degrees. The reason is probably due to the effect of the interference of the blast wave by comparing the blast wave histories at intervals of 10 degrees.

These experimental results should be taken into consideration to ensure a higher degree of safety in the design of underground magazines.

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