Research paper

The effect of structure shape variation of underground magazine on propagation characteristics of blast waves

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Abstract

For the aim of developing more efficient and higher safety for magazines, this study investigated the effect of magazine shapes on the external propagation characteristics of blast waves generated by internal explosions. The experiments were conducted by varying the internal and external volumes of the magazines. The blast wave pressures that propagated around the magazines were measured by piezoelectric sensors. The results show that overpressure of the rear direction decreases significantly as both internal and external volumes increase, whereas the front pressure varied a little.

Keywords : blast wave, magazine, structure shape, peak overpressure, impulse

1. Introduction

A magazine that stores energetic materials requires a high safety factor. A blast wave resulting from an accidental explosion could cause serious damage to structures as well as loss of human life over far distances. With the aim of developing more efficient and higher safety levels for magazines, many studies[1)−14)] have been conducted to investigate the external propagation characteristics of blast waves generated by internal explosions.

Explosives are often stored in an "underground magazine" (UGM), which is a man-made tunnel in the side of a mountain. Usually, a UGM is not destroyed by an explosion because the mountain acts like a massive fortification. Many studies[5)−7), 11)] regarding UGMs' safety design have mainly investigated the effect of a direction and a distance from the exit of the magazine on the propagation characteristics of the blast wave. Some results have shown that a small-scale experiment using one gram has good repeatability[11),15)] and confirm that the scaling law of blast waves is applicable for UGMs[7)]. However, there is little research that focuses on the internal and external shape variations of UGMs.

In this study, in order to investigate the effect of UGM shape variation on the propagation characteristics of blast waves in detail, small-scale experiments were conducted with UGM models exhibiting different external and internal volumes.

2. Experiments

Experiments 1-1 (Exp. 1-1) and 1-2 (Exp. 1-2) were conducted with two kinds of magazine models in order to investigate the effect of different external volumes. Figure 1 shows the UGM model for Exp.1-1 as it was used in a previous study[11)]. External volume is defined by the external surface of the model and its ground surface, as shown by the dotted line. The model was comprised of a steel plate, a cylindrical steel vessel, and a steel cover with a thickness of 3 mm. The model was hollow inside. To best model the steel cover after a mountain, the steel cover was given a pyramid shape with a square base (330 × 330mm), irregular quadrilateral sides, and a flat square (70 × 70mm)

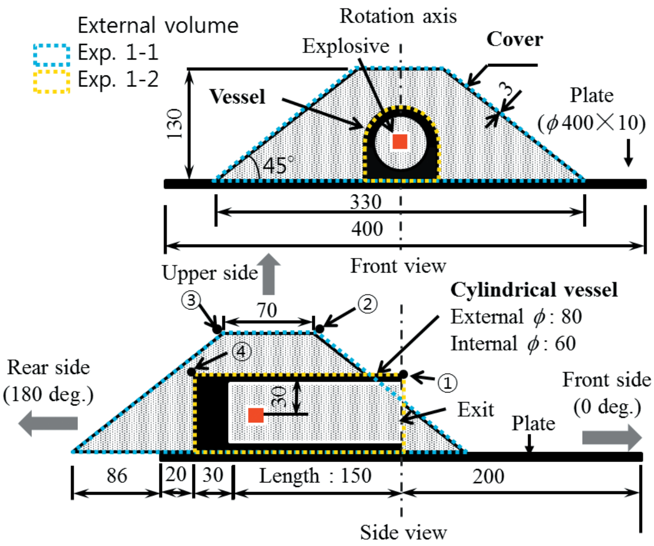

Figure 1 Magazine model for Exp.1-1 (Units : mm).

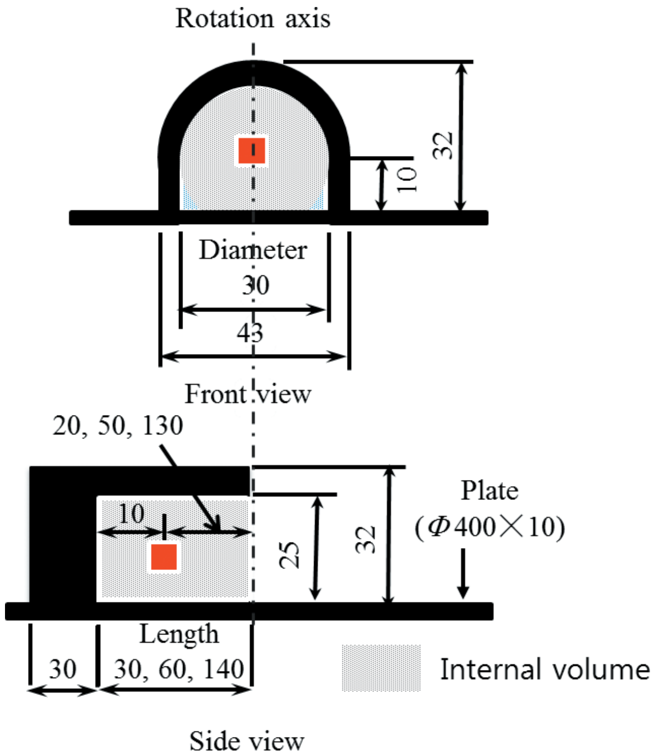

Figure 2 Magazine models for Exp. 2-1, Exp. 2-2, and Exp. 2-3 with different L/D ratios (Units : mm).

on the top. The external volume of Exp. 1-1, which is presented as the blue dotted line in Figure 1, was calculated by using the dimensions of the steel cover. The steel cover and the cylindrical vessel were fixed to the steel plate.

The magazine model used in Exp. 1-2 was the same cylindrical steel vessel that was used in Exp. 1-1. Therefore, Exp. 1-2 was conducted without a steel cover. The external volume for Exp. 1-2, that is presented as the yellow dotted line in Figure 1, was 20% smaller than that of Exp. 1-1. Internal volume is defined as the room inside the model.

Figure 2 shows the models for Exp. 2-1, Exp. 2-2, and Exp. 2-3, which were used to investigate the effect of different internal volumes on the blast wave pressure. The diameter (D) of the exit, while not a perfect circle, was fixed at 30 mm. The lengths (L) inside the vessel varied from 30, 60, and 140 mm for Exp. 2-1, Exp. 2-2, and Exp. 2-3, respectively. Therefore, the ratio of length to diameter (L/D) is 1, 2, and 4.7, respectively, meaning that the internal volumes increased as L/D increased. Table 1 shows the dimensions of L/D and the volumes for each magazine model. The internal volume variations for Exp. 2-1, Exp. 2-2, and Exp. 2-3 were just 1, 2, and 4.7 times, the same as L/D.

Figure 1 shows that explosives were set at the center (15 mm from the vessel bottom) and 135 mm from the magazine exit. Figure 2 shows that explosives were set at 20, 50, and 130 mm from the magazine exit for Exp. 2-1, Exp. 2-2, and Exp. 2-3, respectively. The explosive used in this experiment was approximately one gram of PETN/SR (PETN with silicone rubber as a binder in a ratio of 70 : 30 by weight)[15]. Explosives were ignited by small-size electric detonators (Showa Kinzoku Kogyo Co., Ltd.), which included 0.1 g of lead azide[15]. We confirmed that the steel cover was not deformed by an explosion of the one gram.

The experimental setup and operations performed were the same as those conducted in a previous study[11]. The magazine model was fixed to a steel plate (2000 × 3010 × 10mm) as a ground surface with a damping rubber element (chloroprene) to minimize the vibration generated by the explosion. In order to investigate the attenuation characteristics of the blast waves that propagated around the magazine model, the side-on pressure of blast wave propagating along the ground surface were measured by four piezoelectric sensors (PCB Piezotronics Inc., HM102A), which were located at 0.4, 0.6, 1.1 and 1.7 m from the exit of the magazine model. The UGM model was rotated in order to measure the blast overpressure at different directions in azimuth angle, which is the direction of the sensors measured from the

Table 1 Length and volume dimensions for magazine models.

Exp.	Length / Diameter	Internal volume [mm^3]	External volume [mm^3]	Different shape
1−1	2.5	4.24×10^5	5.93×10^6	External
1−2	2.5	4.24×10^5	1.03×10^6	
2−1	1	1.96×10^4	0.71×10^5	Internal
2−2	2	3.92×10^4	1.07×10^5	
2−3	4.7	9.14×10^4	2.02×10^5	

extended centerline of the magazine[11]. The direction to the front-facing exit of the model is 0 degrees, making the rear-facing direction 180 degrees. Therefore, in order to measure the side-on pressure at the same distance for different directions, the experiments were conducted three times in three directions (0, 90, and 180 degree) or four times in four directions (0, 60, 120 and 180 degree).

3. Results and discussions

3.1 External shape effect

Figure 3 shows the blast wave histories of the side-on pressures at 1.7 m in order to compare the results of the experiments with and without the cover (Exp. 1-1 and Exp. 1-2). The initial time is when the explosives were ignited. Figure 3 (A) shows the blast wave histories of the 0 degree. Even though the peak overpressures (*Ps*) were not significantly different, the time of arrival (TOA) of Exp. 1-1 was clearly faster than the TOA of Exp.1-2. It should be mentioned that measurement error for overpressures was under 10% and TOA margin of error was less than ten microseconds in this experiment. Figure 3 (B) shows the blast wave histories of the 180 degree. The blast wave history that showed a higher peak overpressure and a faster TOA was confirmed in Exp. 1-2. Although all blast wave histories are not shown in this paper, it is confirmed that, in the case of Exp. 1-1 with the cover, the blast wave of 0 degree arrived faster and that of 180 degree arrived later. The causes of these phenomena are discussed later in this chapter.

Figure 4(A) shows the peak overpressure results for Exp. 1-1 (i.e. the model with painted symbols) and for Exp. 1-2 (i.e. the model with unpainted symbols) in relation to the scaled distance. When comparing results, *Ps* for 0 and 90 degree varied little. However, *Ps* of 180 degree for Exp.

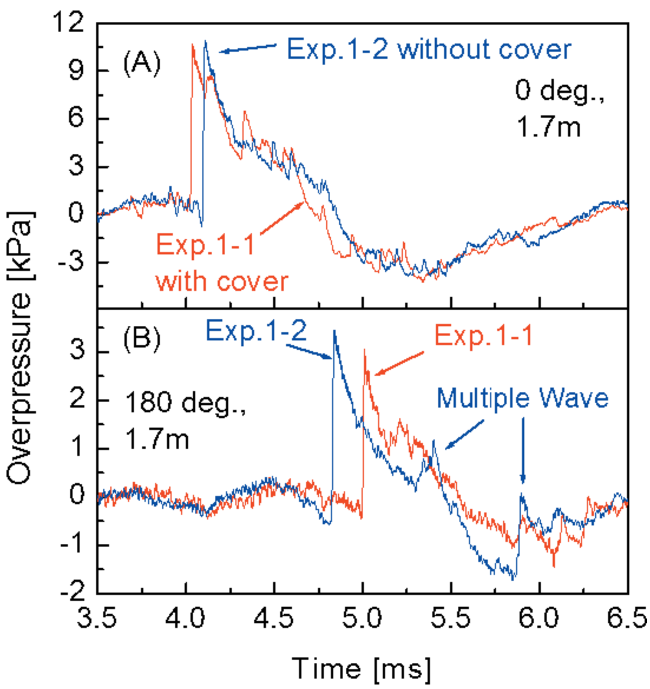

Figure 3 Comparison of blast wave histories for experiment results of Exp. 1-1 with the cover and Exp. 1-2 without the cover from front (A) and rear (B) directions.

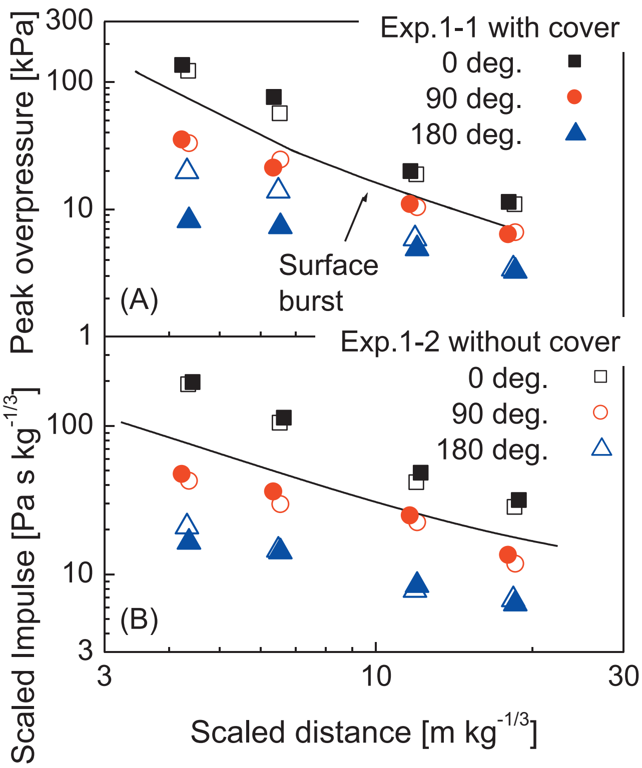

Figure 4 Effect comparison of different external volumes on peak overpressure (A) and impulse (B) for Exp. 1-1 (Painted symbol) and Exp. 1-2 (Unpainted symbol).

1-1 with the cover decreased significantly, especially at closer distances.

Figure 4(B) shows the experimental results for scaled impulse (*Imp*). The effect of the shape on the impulse for 0 and 90 degree was not significantly different, as similar to that for *Ps*. However, the effect for 180 degree was not significantly different neither, even though the peak overpressure was clearly decreased.

Previous studies[7), 11),12)] report that the blast wave overpressure was decreased dramatically by an obstacle, especially at a closer distance from the obstacle. Furthermore, although there is some directionality near an obstacle, it would disappear at distance due to the diffraction of the blast wave[11)]. However, it is not clear the attenuation mechanism of blast wave overpressure.

In this study, it is considered that two complex phenomena occurred. One is that the propagation distance is different depending on the model's volume. It is well known that, as a blast wave propagates over a further distance, the overpressure decreases and TOA comes later. The TOA of 180 degree for Exp. 1-2 is faster than that for Exp. 1-1, as shown in Figure 3 (B). Regardless of the different external volumes of the models, the linear scaled distances (*SD*) from the model's exit to the pressure sensors are the same. However, it should be mentioned that blast waves propagate along the surface of the model. Therefore, in the case of Exp.1-1 having a greater volume, the blast wave propagated a further distance than the distance for the smaller volume model of Exp.1-2. It is considered that the different propagation distance of the blast wave should cause the different TOA.

In order to investigate the effect of different

Table 2 Estimated values and experiment results for peak pressure of 180 degree.

SD [m kg$^{-1/3}$]	$Ps_{.F}$ [kPa]	Estimated values: Exp.1−1 (with cover) $SD_{.E}$ [m kg$^{-1/3}$]	Exp.1−1 (with cover) $Ps_{.E}$ [kPa]	Exp.1−2 (without cover) $SD_{.E}$ [m kg$^{-1/3}$]	Exp.1−2 (without cover) $Ps_{.E}$ [kPa]	Experiment results: Exp.1−1 $Ps_{.R}$ [kPa]	Exp.1−2 $Ps_{.R}$ [kPa]
4.3	74.2	5.6	43.8	5.2	51.5	8.2	19.8
6.5	32.8	7.8	23.9	7.4	26.1	7.3	13.9
11.9	12.7	13.2	10.5	12.8	11.5	4.9	5.9

$Ps_{.F}$: Ps for surface burst.
$SD_{.E}$: Estimated SD of which blast propagates along the model surface.
$Ps_{.E}$: Estimated Ps for surface burst at $SD_{.E}$.
$Ps_{.R}$: Measured Ps in this experiment.

propagation distance, Table 2 shows estimated values and the experiment results for Ps of 180 degree, respectively. The estimated values are the estimated scaled distance ($SD_{.E}$) and estimated peak overpressure ($Ps_{.E}$). Here, $SD_{.E}$ were calculated with considering the propagation distance on model's surface. And $Ps_{.E}$ were calculated with considering the blast wave for free surface explosion at each $SD_{.E}$. For example, SD and Ps of the sensor at 0.4 m are 4.3 m/kg$^{1/3}$ and 74.2 kPa in case of free surface explosion. In case of the Exp.1-1, $SD_{.E}$ becomes 5.6 m/kg$^{1/3}$, and $Ps_{.E}$ will be 43.8 kPa. In case of Exp.1-2, the $SD_{.E}$ and $Ps_{.E}$ have 5.2 m/kg$^{1/3}$ and 51.5 kPa. It means that Ps decrease 43.8 kPa and 51.5 kPa as SD increase 5.6 m/kg$^{1/3}$ and 5.2 m/kg$^{1/3}$. However the experiment results ($Ps_{.R}$) of 8.2 kPa and 19.8 kPa are greatly smaller than the estimated value of 43.8 kPa and 51.5 kPa. Therefore, it is concluded that the effect of the different propagation distance is not only the reason for attenuation of the blast wave pressure.

The other possibility is the diffraction effect. It is considered that the blast wave was diffracted at a bent surface of the model[14),16),17)]. The points ①–④ in Figure 1 display the area where the blast wave was diffracted. Regardless of the different external volume, the pressure inner the vessel is the same until the exit of the point ①. In the case of Exp.1-1, the blast wave was diffracted three times at the point ①, ② and ③ along the line at 45 degree. In the case of Exp.1-2, the blast wave was diffracted two times at the point ① and ④ along the line at 90 degree. It is considered that the blast wave pressure would be decreased because the degree of an angle increase while the blast wave was diffracted in several times. Further study is required to investigate quantitatively the effect of an angle on the attenuation of the overpressure.

Another concern is that why Ps for Exp.1-1 of 180 degree is lower than Ps for Exp.1-2 at closer distance. And, why Imp are not significantly different even though Ps are different clearly at closer distance.

The mechanism is not clear, but the clue is found in previous study[11)] which was reported that there are multiple peak of time histories of the blast wave pressure at rear side. In this study, the multiple peak are also confirmed in Figure 3.

After the blast wave was diffracted at the exit, the diffracted wave propagates in every direction. The diffracted wave propagates along the ground surface, and it also propagates along the rooftop of the models such as the line of the point ①, ② and ③. Finally, the diffracted wave will get together at rear side. It is considered that the peak overpressure would be directly affected by the diffraction because Ps is an instantaneous pressure. Meanwhile, the impulse would be not, because the impulses were recorded as the time-integration of the overpressure during the positive pressure phase. It is considered that the attenuation behaviors of the peak overpressure and the impulse are different because there are multiple waves propagate at the rear side. Our further study with a calculation simulation is investigating the propagation behavior the blast wave at the rear side.

3.2 Internal shape effect

In order to investigate the effects of the internal shape on blast wave pressure, Exp. 2-1, Exp. 2-2, and Exp. 2-3 were conducted using multiple models of varying lengths (L/D of 1, 2, and 4.7). Figure 5(A) shows the blast wave histories of 0 degree at 0.4 m. The fastest TOA and the highest peak overpressure were confirmed to be in the model with an L/D ratio of 2. It should be recognized that the distances from the initial point of the explosives to the pressure sensors at 0.4 m were 0.42 m when L/D was 1 and 0.45 m when L/D was 2. Before conducting this experiment, it was believed that the fastest TOA and highest peak overpressure would be found in the L/D ratio of 1 because the blast wave propagation distance was shorter. Another interesting phenomenon was found in the blast wave histories for 1.1 m. Figure 5 (B) shows that the TOA for the L/D ratio of 2 was still the fastest. However, it is also confirmed to have the lowest peak overpressure. It is challenging to understand why the model with the L/D ratio of 2 presented the lowest peak overpressure even though its TOA is the fastest. The blast wave histories of 180 degree were recorded in Figure 5 (C). The higher peak overpressure and faster TOA are confirmed to correlate with the lower L/D ratio.

In order to investigate the effect of L/D on blast wave pressure, Figure 6 illustrates the peak overpressures with

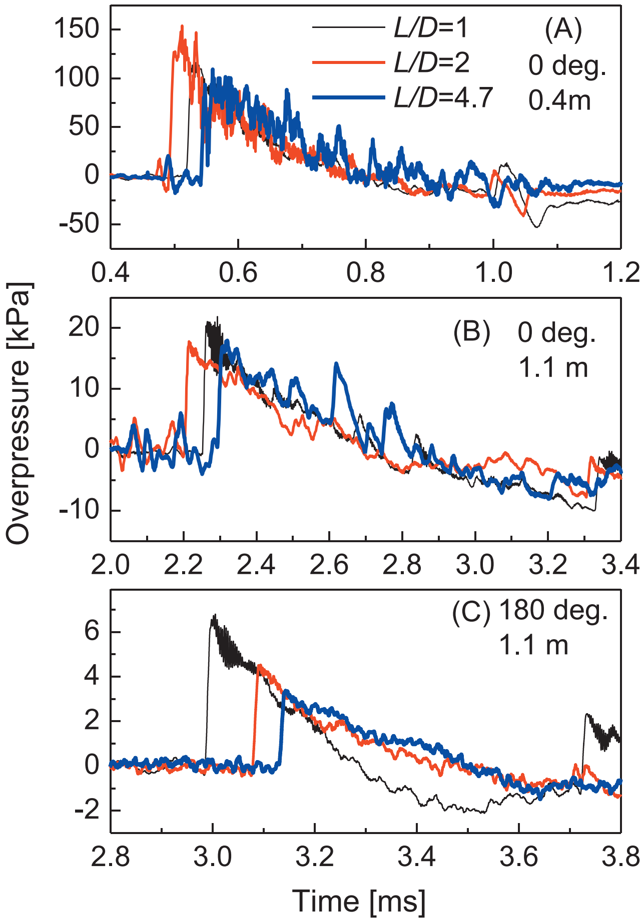

Figure 5 Comparison of blast wave histories between 0.4 m and 0 degrees (A), 1.1 m and 0 degrees (B), and 1.1 m and 180 degrees (C) where L/D is 1, 2, and 4.7 for Exp. 2-1, Exp. 2-2, and Exp. 2-3, respectively.

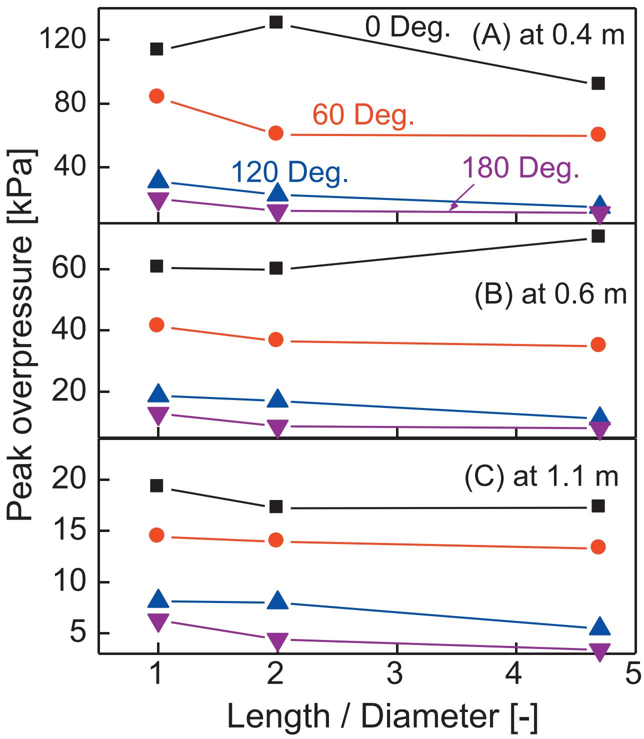

Figure 6 Peak overpressure observed when L/D was 0.4 m (A), 0.6 m (B), and 1.1 m (C) for Exp. 2-1, Exp. 2-2, and Exp. 2-3, respectively.

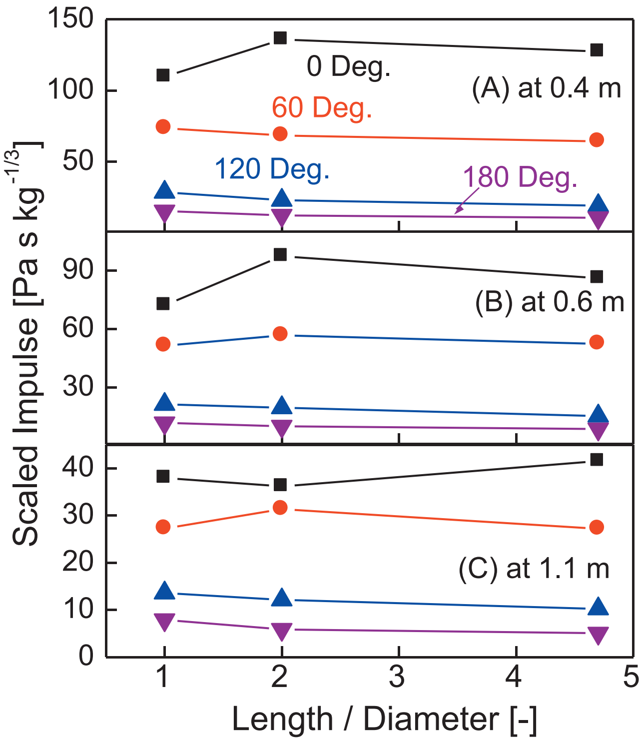

Figure 7 Scaled impulse observed when L/D was 0.4 m (A), 0.6 m (B), and 1.1 m (C) for Exp. 2-1, Exp. 2-2, and Exp. 2-3, respectively.

respect to the L/D ratio per 60 degrees. As L/D increases, the peak overpressures at 60, 120, and 180 degrees decrease continuously. However, the peak overpressures for 0 degrees at 0.4 m increase and decrease. Furthermore, the peak overpressures for 0 degrees at 0.6 m increase continuously.

Figure 7 shows the scaled impulse with respect to L/D. Not only the peak overpressure, but also the impulses have the same tendencies. As L/D increases, the impulses for 120 degrees and 180 degrees decreased continuously. However, the impulses for 0 degrees and 60 degrees did not decrease continuously. For example, the impulse for 0 degrees increases and decreases while L/D increased.

It is thought that the strength of the blast wave pressure decreases as L/D increases. However, the results of this experiment show that the overpressure observed at the front-facing direction did not decrease continuously as L/D increased. Unfortunately, the reason for this discrepancy is not clear in this study. Further studies has been conducting with numerical calculations.

4. Conclusions

This study investigates the effect of structures shape variation of an underground magazine on external propagation characteristics of the blast waves that are generated by an internal explosion. This study used two kinds of magazine models for different external volumes and three kinds of models for different internal volumes.

The experimental results using different external volumes show that an increase of external volume caused the peak overpressures for 0 and 90 degrees to decrease a little. However, the peak overpressures for 180 degrees decreased significantly, especially when measured at closer distances. Attenuation tendencies of the impulse differ from the peak overpressure. The effect of using different volumes on the impulse was smaller. Due to an increase of external volume, the impulses for 0 degree and 90 degrees were a little higher whereas the impulses for 180 degrees decreased a little.

The experimental results using different internal volumes show that attenuation tendency of blast wave pressure is not correlated with varying the internal volumes. Results show that the blast wave overpressures at 120 degrees and 180 degrees decreased as the magazine length increased. However, the overpressures measured at 0 degree and 60 degrees did not depend on the length. It increased or decreased as length increased. Both peak overpressure and the impulse had the same tendency. The reason is not clear in this study. Further studies will be conducted with numerical calculations.

The results of these experiments are worth taking into consideration in order to design underground magazines with a higher degree of safety.

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