Research paper

On the azimuth angle characteristics of the blast wave from an underground magazine model (I) -Experiment with a magazine of small ratio of the length to the inner diameter-

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Received : April 8, 2016 Accepted : July 5, 2016

Abstract

We conducted small-scale explosion experiments to determine the azimuth angle characteristics of the blast wave from an underground magazine model inside a cover model and discuss its difference in cases with and without a dike model. The magazine comprised a cylindrical steel pipe with one end closed by a fixing jig, and the ratio of the length to the inner diameter was 3. The overpressures of the blast wave were measured using piezoelectric pressure sensors that were placed in twelve locations on the steel plate. The magazine and the cover models were set on a rotary table that changed the azimuth angles of the magazine exit and the pressure sensors between 0 and 180° in intervals of 10°. A series of explosion experiments provided the azimuth angle characteristics of the blast wave from the exit. The increment of the azimuth angle induces a reduction in the peak overpressure. In the present study, we observed two additional phenomena that changed blast wave strength. One was the local geometrical irregularity of the cover model that enhanced the blast wave behind the magazine. The other was the reflection and the diffraction of the blast wave at the dike that enhanced and attenuated the blast wave. We propose an empirical formula that includes the above effects, which can properly estimate the azimuth angle characteristics of a blast wave. The results demonstrate the applicability of the azimuth angle characteristics around an underground magazine.

Keywords : small-scale experiment, blast wave, azimuth angle characteristics, underground magazine

1. Introduction

High explosives instantly release a large amount of energy and are widely used in industrial operations such as mining and blasting excavation. However, an unexpected explosion generates a blast wave, the peak overpressure of which causes damage with a severity that is dependent on the distance between the magazine where the explosive is stored and the adjacent residential area. Therefore, appropriately regulating how high explosives are stored in a magazine is necessary.

An underground (tunnel-type) magazine, which is constructed inside the ground, is regulated in Japan. The regulation says that the explosives safety quantity-distance (ESQD) should be uniformly secured from the outside wall of the underground magazine to the residential area, and that the dike should be located ahead of the exit to minimize the effect of the blast wave and fragments. The ESQD is estimated from the peak overpressure, one of the most important blast parameters. However, in an underground magazine, after a high explosive is detonated, the generated blast wave exits the underground magazine via the opening, and the blast wave strength exhibits azimuth angle characteristics. The blast wave along the exit direction exhibits the highest peak overpressure, and an increment in the azimuth angle from the exit direction results in a weakening of the blast wave. The reflection and diffraction at the dike disturb the blast wave and may change the azimuth angle characteristics considered for the regulation using the ESQD. This may result in shortening of the ESQD behind the magazine exit and lengthening ahead it.

There are many parameters for determining the blast wave strength[1)−7)] from the underground magazine. For example, the peak overpressure depends on the size of magazine chamber (a room in which a high explosive is stored) and tunnel (a passageway to the magazine chamber from exit), loading density (ratio of the stored mass of explosive to the volume of the magazine chamber), etc. Previous studies[2),8),9)] indicated that only the peak overpressure of the shock wave at the magazine exit determines the strength of the blast wave outside. Skjeltorp et al.[1)] studied the azimuth angle characteristics of the blast wave and proposed empirical equations in which the attenuation index of the peak overpressure versus the scaled distance was constant for all azimuth angles. This assumption is used in the safety standard of DDESB[10),11)].

In the present study, we investigated the blast propagation around a small-scale underground magazine model to clarify the difference in the azimuth angle characteristics of the blast wave in cases with and without a dike.

2. Experimental

2.1 Test explosive

A pressed pellet made of pentaerythritol tetranitrate (PETN) and carbon powder was used as an explosive. The pellet consisted of 95 wt.% PETN and 5 wt.% carbon powder. The average cylindrical pellet was 7.55 mm long with a diameter of 7.64 mm. The pellet weight and the density were 0.50 g and 1440 kg m^{-3}, respectively. Two pellets were glued together to form a long cylinder used as a 1.00 g pellet. Our data, as well as those from our previous paper[9),12)], incorporate a scaled distance K, m $kg^{-1/3}$, scaled by the mass of the explosive. 1 m $kg^{-1/3}$ corresponds to 100 mm. A specially designed electrical detonator with 100 mg of lead azide was used. Showa Kinzoku Kogyo Co. Ltd. supplied the explosives and detonators. 4 kV was applied to initiate the detonator using a firing system (FS-43 ; Teledyne RISI, Inc.).

2.2 Setup

Figure 1 shows (a) schematics of the magazine, cover, and dike models, and (b) the position of the magazine and the piezoelectric pressure sensors (PCB 113B28, 100 mV·psi^{-1}) on the steel plate with a thickness of 10 mm. The steel plate will be described as the ground. The blast wave pressures were recorded using a digital waveform recorder (H-TECH Triple mode 30622). The magazine was modeled using a cylindrical steel pipe with one end closed by a fixing jig. The inner diameter, inner length, and wall thickness of the magazine model were 38.8, 117.6, and 6 mm, respectively. The ratio of the length (L) to the inner diameter (D) was $L/D = 3$. We defined that 1/3 of the length of the cylindrical steel pipe from the closed end was considered as the chamber, whereas 2/3 from the exit was the tunnel. The ratio of the cross-sectional area of the tunnel (A_t) to that of the chamber (A_c) was $A_t/A_c = 1$. The chamber was located inside the cover model in which clay with a density of 2230 kg m^{-3} was filled. The center of the explosive was placed at 98 mm inside the magazine exit, and the detonator was glued onto the top of the pellet as shown in Figure 1a. The height of the cover model was 129 mm, and the size on the ground was 349.2×284 mm. The coordinate (x, y) in the present study is defined in Figure 1b, and the origin is located at the exit of the magazine model on the steel plate. The azimuth angle in the counterclockwise direction is defined from the $+x$ direction as shown in Figure 1b. The distances between the magazine exit and pressure sensors on the ground were 400, 800, 1200, and 1600 mm, whose scaled distances are 4, 8, 12, and 16, respectively. The magazine model was set on a rotary table that changed the azimuth angles between the magazine exit and the pressure sensors. Since the magazine model is symmetric at the x axis, the azimuth angle was changed between 0 and 180° in intervals of 10°. The parameter was the presence or absence of the dike model. When the dike is used, the blast wave from the magazine exit reflects and diffracts off the dike, which may change the azimuth angle characteristics.

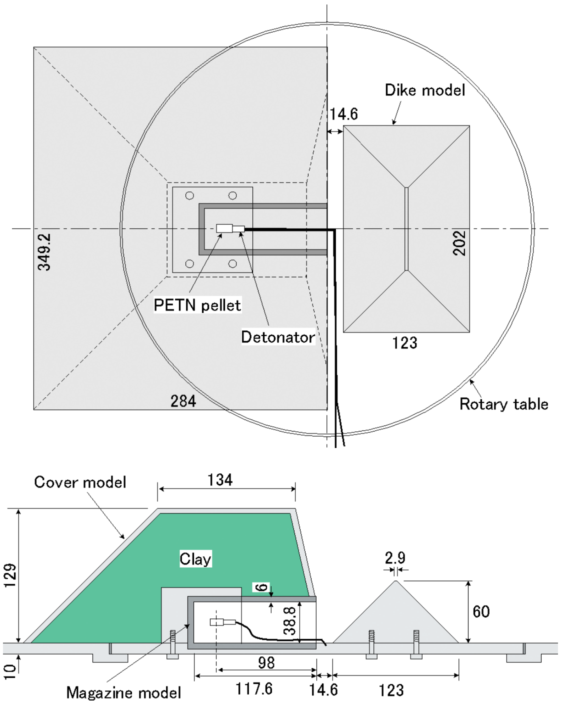
In addition, we conducted surface explosion experiments on a steel plate without models in order to discuss the enhancement and attenuation of the blast wave by the magazine and dike models. The high explosive was placed vertically, and the height between its center and the steel plate was 0.18 m $kg^{-1/3}$.

A series of explosion experiments can confirm the reproducibility of the peak overpressure and could provide the azimuth angle characteristics of the blast wave from the exit. Data in the present paper are the averaged values of 2 or 3 experiments.

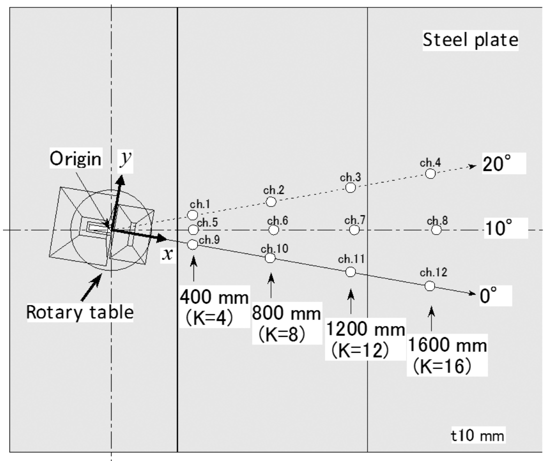
3. Results and discussion

In order to present the azimuth angle characteristics of the blast wave, the overpressure time histories at scaled distances of 4, 8, 12, and 16 at 0, 90, and 180° in cases with (w/) and without (w/o) a dike are shown in Figure 2 as examples. Figure 3 shows the relationship between the peak overpressure and the azimuth angle. The time histories were interpolated using smooth cubic natural spline functions to obtain the peak overpressure which is an important parameter for regulating how a magazine stores high explosives. Standard lines in Figure 3 denote the peak overpressure in the case of a surface explosion on a steel plate without any models and show enhancement and attenuation of the blast wave by the magazine and the dike models.

First, we will separately consider the data with and without the dike. When the blast wave arrives at the pressure sensors, the overpressure increases discontinuously, and peak overpressure is observed. The volumetric expansion of the flow behind the blast wave gradually decreases the overpressure. As the scaled distance increases, the blast wave expansion produces a



(a)



(b)

Figure 1 (a) Schematics of the magazine, cover, and dike models. (b) Position of the magazine and the piezoelectric pressure sensors on the ground.

decrease in the peak overpressure. An increase in the azimuth angle produces a delay in the time-of-arrival, and a decrease in the peak overpressure, which denotes that the diffraction from the exit weakens the blast wave. In our experiments, the maximum peak overpressure did not appear at 0° as shown in Figure 3a ; this may be due to the shape of the magazine model with $L/D=3$. In previous studies[1), 2), 8)], L/D was considered to be large enough to produce a planar shock wave at the exit. In our model, the shock wave at the exit may not be planar but a multi-dimensional wave that comprises an incident shock wave, a Mach stem, and transverse waves that propagate perpendicular to the shock front. Then, a local difference in the blast wave strength appears especially at $K=4$. The peak overpressure around 180° increases locally. Since the cover model is symmetrical and has an angular shape as shown in Figure 1, the blast wave from both sides ($+y$ and $-y$ sides) behind the cover model couples and strengthens. This indicates that the local geometrical irregularity of the natural terrain is an important factor in estimating the blast wave strength.

Next, we will compare results with and without the dike in Figures 2 and 3. When the blast wave propagates to the dike, diffraction and reflection of the blast wave will occur, and therefore, the diffraction effect appears ahead of the dike (small azimuth angle), whereas the reflection effect occurs behind the dike (large azimuth angle). The effect of the diffraction is obviously observed for the peak overpressure around 0° as shown in Figures 2a, 2b, and 3a. It was 2/3 times that without the dike at $K=4$. However, the diffraction effects no longer appear at large scaled distances. As previously mentioned by Sugiyama et al.[12)], after the blast wave crosses the dike, the locally curved blast wave reflects off the ground, resulting in local pressure recovery far from the dike. Therefore, blast wave mitigation by the dike is limited only near the dike as shown at $K=4$ and 8 of Figure 3 near 0°.

The effect of the reflection off the dike is obviously observed on the peak overpressure over 90° as shown in Figures 2c-f and 3. At the maximum condition, the dike makes the peak overpressure 2.5 times larger at $K=4$ and 180°. The reflection at the dike generates a secondary shock wave that catches up with and enhances the incident blast wave behind the magazine, and the peak overpressure increment continues to large scaled distances.

The above effect produces the magnitude relation change of the peak overpressures in the cases with and without a dike at an azimuth angle of around 70°.

The peak overpressure, p_{peak}, as functions of the azimuth angle, θ, and index, n, were used to investigate the characteristics of the blast wave. The peak overpressure is expressed by the following equation proposed by Skjektorp et al.[1)] :

$$p_{peak}(\theta)=\frac{p_{peak}(0)}{\left[1+\left(\frac{\theta}{a_1}\right)^{n_1}\right]}. \quad (1)$$

Parameter a_1 is determined from the azimuth angle in the case of $p_{peak}(a_1)=0.5\, p_{peak}(0)$. n_1 denotes the attenuation constant. Skjektorp et al.[1)] proposed $a_1=56^{\circ}$ and $n_1=2.0$ to cover a wide range of the distance from the exit. Nakayama et al.[6)] showed that $a_1=98.3^{\circ}$ and $n_1=2.0$ for a scaled distance of 16 m kg$^{-1/3}$. Kim et al.[7)] showed that $n_1=2.3$ and that a_1 increased with an increase in the scaled distance. In our study, we tried to utilize the effects of the reflection of the blast waves from the $+y$ and $-y$ side at 180° and the reflection off the dike and in Equation (1), and simply added the second term of the former effect and the third terms of the latter effect as

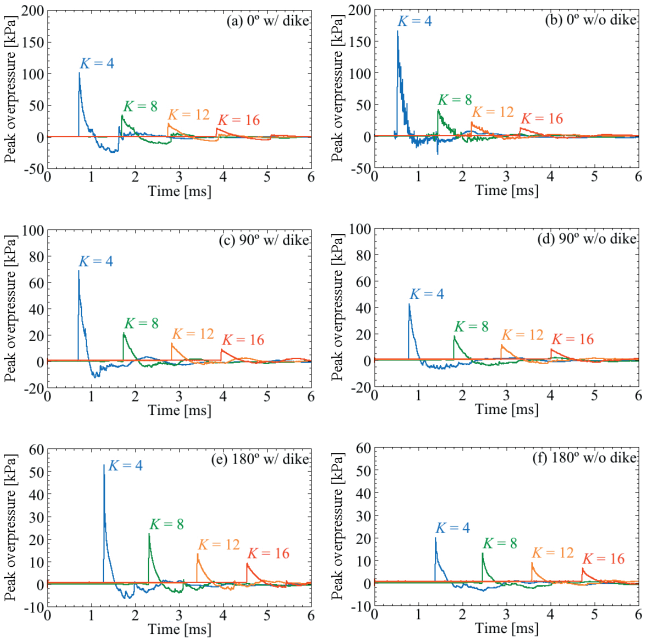


Figure 2 Overpressure time histories at scaled distances of 4, 8, 12, and 16 at 0, 90, and 180° in cases with (w/) and without (w/o) the dike.

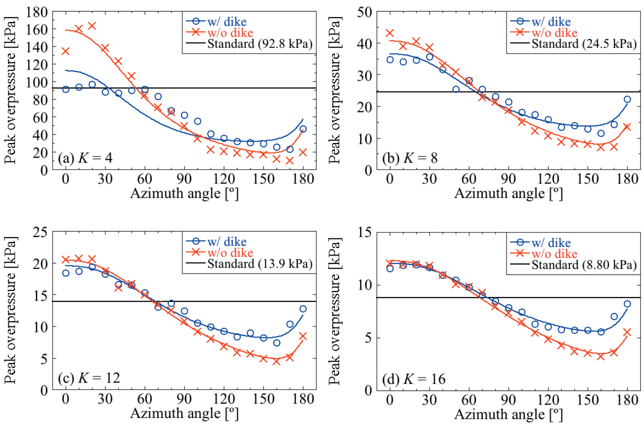


Figure 3 Peak overpressure distribution.

$$p_{peak}(\theta) = p_{peak}(0)\left\{\frac{1}{\left[1+\left(\frac{\theta}{a_1}\right)^{n_1}\right]}+\frac{1}{\left[1+\left(\frac{\theta}{a_2}\right)^{n_2}\right]}+\frac{1}{\left[1+\left(\frac{\theta}{a_3}\right)^{n_3}\right]}\right\}. \quad (2)$$

Here, in order to separately and universally estimate the two terms in Equation (2), we assumed that $p_{peak}(0)$ is the primary parameter, a_1 is constant in the cases with and without the dike, and a_2, a_3, n_1, n_2, and n_3 are independent of the scaled distance and the presence or absence of the dike. Table 1 shows the parameters in the present study. Since $p_{peak}(0)$ is smaller, the azimuth angle of a_1 becomes relatively larger by increasing the scaled distance. The lines from Equation (2) are described in Figure 3. At 4 m kg$^{-1/3}$ with the dike, the blast wave is strongly disturbed by the dike, and the curve does not agree with the experimental data. At 4 m kg$^{-1/3}$ without the dike, the blast wave is not well developed, and the curve does not agree with the experimental data around 180°. Then, we will not discuss the azimuth angle characteristics using Figure 3a. As the blast wave is well developed at a large scaled distance, other lines agree well with the experimental data. Our proposed Equation (2) indicates that the effects of the reflections of the blast waves from the $+y$ and $-y$ side at 180° and the dike can be separately considered and that a_2, a_3, n_1, n_2, and n_3 are universal constants in the present underground magazine model at $K \geq 8$.

Now, we will state the applicability of the parameters listed in Table 1. Nakayama et al.[6] and Kim et al.[7] used a steel magazine of $L/D = 2.6$ and 2.5, respectively, which are almost equivalent to the present study ($L/D = 3.0$). $a_1 = 98.3$ and $n_1 = 2.0$ from Nakayama et al. was obtained from the limited data for 0, 60, 120, and 160°. Additional data for the different azimuth angles can modify the parameters proposed by Nakayama et al.[6] and can describe different line. When we applied the parameters a_1, a_3, n_1, and n_3 from their data between 0 and 160°, we confirmed that our line can properly reproduce their experimental data. The observation that a_1 depends on the scaled distance and $n_1 = 2.3$ from Kim et al.[7] also agrees with the present data. However, the values $a_1 = 56°$ and $n_1 = 2.0$ reported by Skjeltorp et al.[1] are quite different from those in the present study. This may be due to the magazine shape, such as A_t/A_c and L/D. Skjeltorp et al. used a steel magazine of $L/D = 86$ without the ground. The planar shock wave is well developed in the tube, and the blast wave emerging from a long pipe tends to exhibit spherical expansion. As shown in Figure 1b, the blast wave propagates on the ground in the present study, and the hemispherical expansion then produces a weaker attenuation of the peak overpressure as a function of the azimuth angle than that of Skjeltorp et al.[1], and a_1 tends to be larger. The above previous studies denote that the parameters in Equation (2) are functions of

Table 1 Parameters for Equation (2).

Scaled [m kg$^{-1/3}$]	dike	$p_{peak}(0)$ [kPa]	a_1	n_1	a_2	n_2	a_3	n_3	Correction coefficient, R^2
4	w/o	158.1	61.9	2.3	192.0	−21.0	–	–	0.959
8		40.6	82.1						0.989
12		20.4	92.0						0.993
16		12.3	102.3						0.991
4	w/	112.3	61.9	2.3	192.0	−21.0	360.0	−1.8	0.765
8		36.5	82.1						0.955
12		19.5	92.0						0.969
16		12.1	102.3						0.983

Table 2 Fitting parameters for Equation (4).

Azimuth angle θ	w/o dike			w/ dike		
	l	m	n	l	m	n
0°	2.95813	−1.19122	−0.30628	2.64168	−0.94571	−0.30384
10°	3.63633	−2.64998	0.44334	2.78927	−1.29225	−0.10868
20°	3.58942	−2.50120	0.35026	2.79048	−1.25834	−0.13379
30°	3.39554	−2.23573	0.25235	2.50464	−0.65741	−0.44899
40°	3.58269	−2.83698	0.59807	2.78018	−1.34356	−0.08819
50°	3.19521	−2.07006	0.21190	3.39681	−2.84127	0.73154
60°	2.98324	−1.86055	0.17206	3.13129	−2.11400	0.28203
70°	3.12285	−2.44439	0.54576	3.19661	−2.37616	0.42555
80°	2.88537	−1.92840	0.23868	2.76307	−1.59857	0.06849
90°	2.56428	−1.48621	0.06293	2.75142	−1.65568	0.10050
100°	2.29504	−1.26264	0.02600	3.00304	−2.42715	0.54680
110°	1.59182	−0.10259	−0.50113	2.14721	−0.66402	−0.37541
120°	1.78518	−0.63250	−0.23419	2.07769	−0.65648	−0.34885
130°	2.02481	−1.33610	0.15010	2.24667	−1.24855	−0.01548
140°	1.71768	−0.67663	−0.22100	1.98481	−0.64745	−0.30287
150°	1.81750	−0.89880	−0.13104	2.16536	−1.16247	−0.00370
160°	1.29850	−0.07194	−0.48638	2.20906	−1.44825	0.19462
170°	0.82040	0.81193	−0.85498	1.43807	0.25432	−0.61390
180°	1.00735	1.17734	−1.15980	1.96992	−0.13987	−0.61096

the shape of the magazine, etc. Therefore, it is important to understand their effects, and these will be investigated further in future studies.

In order to obtain the peak overpressure distribution, the relationship between the peak overpressure and the scaled distance of each experimental condition was fitted using quadratics as a log-log plot to obtain the averaged and representative curve for comparison. The obtained fitting parameters are l, m, and n of the following equations :

$$X = \log K, \tag{3}$$

$$\log(p_{peak}) = l + m\mathrm{X} + nX^2. \tag{4}$$

Table 2 presents the fitting parameters obtained in the present study. Now, we will show the isobaric lines of the peak overpressures of (a) 92.8 kPa, (b) 24.5 kPa, (c) 13.9 kPa, and (d) 8.80 kPa in cylindrical coordinates of scaled radius and azimuth angle, to discuss the ESQD from the magazine exit as shown in Figure 4. The above peak overpressures are obtained by the scaled distance of $K = 4$, 8, 12 and 16 in the case of the surface explosion experiments as shown in Figure 3. The black solid line denotes the isobaric line of the surface explosion experiments from the ignition point. Since the hemispherical blast wave uniformly expands from the ignition point, the isobaric line forms a semicircle. The dashed and solid colored lines denote the isobaric lines in the cases with and without the dike. The origin in radial direction is located at the magazine exit, and the azimuth angle characteristics appears as shown in Figure 4. When colored data is located outside the black solid line, the blast wave from the underground magazine model is stronger than that of the surface explosion experiments. Regardless of the presence or absence of the dike, the peak overpressures at azimuth angles between 0 and 70° were larger than those of the surface explosion. Our data agree with those of Nakayama et al.[6], who conducted large-scale explosion experiments of the underground magazine model without the dike model, and showed that the peak overpressures at azimuth angles of 0 and 60° were approximately equal or larger than that of a surface explosion. The diffraction effect of the dike is limited only near the dike, and the reflection effect of the dike continues to appear at a larger scaled distance as mentioned above. Additionally, around 180°, the local enhancement of the blast wave appears, but the overpressure is still smaller than that of the surface explosion. We should carefully consider the effects of the dike and the geometrical irregularity for the determination of the ESQD.

The process for the estimation of the blast wave strength against the azimuth angle can be applied for the determination of the ESQD of an underground magazine. Experimental data denotes that the present underground magazine model lengthens the ESQD between 0 and 70°. Previous studies[2), 8), 9)] showed that the exit overpressure could scale the blast wave strength from the exit, and that the exit overpressure can be reduced by a smaller loading density and a larger L/D. We will conduct a parametric study in order to design a new underground magazine shape to shorten the ESQD at all azimuth angles.

4. Conclusions

We conducted small-scale explosion experiments to determine the azimuth angle characteristics of the blast wave from an underground magazine model in cases with and without a dike. The ratio of the length to the inner

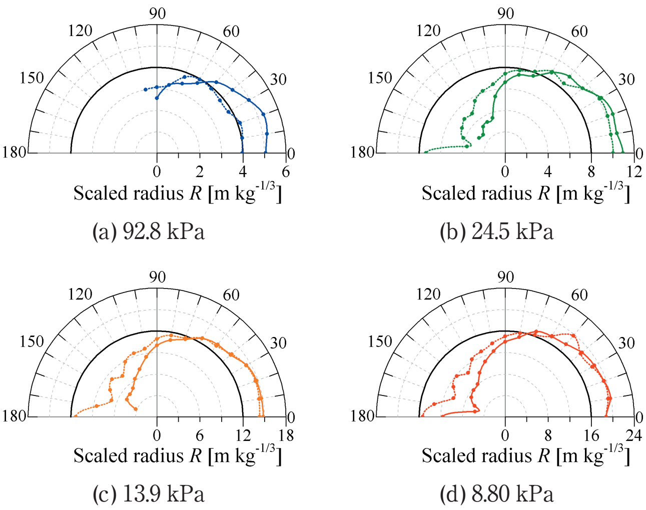


Figure 4 Isobaric lines of the peak overpressure of (a) 92.8 kPa, (b) 24.5 kPa, (c) 13.9 kPa, and (d) 8.80 kPa in cylindrical coordinates of scaled radius and azimuth angle. The above peak overpressures are obtained by the scaled distance of 4, 8, 12 and 16 in the case of the surface explosion experiments as shown in Figure 3. The black solid line denotes the isobaric line of the surface explosion experiments from the ignition point, and the dashed and solid colored lines denote the isobaric lines in the cases with and without the dike from the magazine exit.

diameter in the magazine, L/D, was 3. The dike produces the effects of reflection and diffraction of the blast wave. The reflection enhances the blast wave behind the magazine, whereas the diffraction weakens it ahead of the magazine near the dike. The geometrical irregularity of the cover model induces the local enhancement of the blast wave around 180°. We proposed an empirical equation that includes the reflection effects, which can properly estimate the blast wave strength as a function of the azimuth angle. The parameters in the equation are universal constants in the present underground magazine model. The process for the estimation of the blast wave strength against the azimuth angle can be applied for the determination of the ESQD of an underground magazine.

Acknowledgement

This study was made possible by a METI (Ministry of Economy, Trade, and Industry) sponsored project named "technical standard for explosion mitigation of explosives" in FY2015.

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