Research paper

# Propagation and attenuation characteristics of blast wave pressure generated from an explosion inside an earth-covered magazine

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## Abstract

This paper reports on a field experiment conducted to investigate the propagation and attenuation characteristics of a blast wave generated by an explosion inside a magazine model that was based on an earth-covered magazine with a barricade (ECM). The magazine models were constructed of reinforced concrete with an earth cover so that they would be destroyed by an explosion. The blast wave pressures were measured by piezoelectric sensors set up at different distances and directions from the exit of the ECM. The results of the experiment showed that the blast wave pressures resulting from an explosion within an ECM are significantly lower in comparison with those for a surface burst—with the average values of equivalent weight being approximately a tenth of the explosive weight for a surface burst. It was also found that up until $40\,m\cdot kg^{-1/3}$ there is some directionality in blast wave propagation. Based on the results of different scale experiments, we conclude the paper with a discussion of the applicability of scale law for blast wave pressure.

***Keywords*** : earth-covered magazine, blast wave, directionality, scale effect

## 1. Introduction

A magazine in which energetic materials are stored needs a high safety factor to mitigate the effects of an accidental explosion. From the point of view of safety, the attenuation and the propagation characteristics of blast waves need to be studied to prevent damage to structures as well as the loss of human life. Recently, with the aim of developing more efficient and higher safety at magazines, many studies[1)−7)] have been conducted that investigated blast waves originating from accidental explosions at magazines. However, most of these studies focused on underground magazines (UGM)[1)−4)], and although a few studies[5)−7)] have been made of earth-covered magazines (ECM), most of them have investigated ECMs in the United States, and not in Japan. The main point of interest is that the roof thickness of an ECM in Japan is 3 m, whereas it is 0.61 m in the United States. As different roof thicknesses likely effect the propagation behavior of blast waves, a study of ECMs of Japan is required.

About 50 years ago, an experiment-based study of ECMs in Japan was conducted by the Ministry of International Trade and Industry (MITI)[8), 9)]. In the experiment, blast wave pressure was measured by a "blast meter," which consisted of a lead plate mounted on supports. The deformation of the supported lead plate was measured after the blast wave propagated. Compared to recent measurement technology, it is considered that the blast meter used at that time did not give enough accuracy, meaning that a quantitative analysis had not been conducted sufficiently well.

In Japan, there is an earth bank in front of the exit of an ECM, but in the United States a barricade is used to prevent scattering of fragments of the exit door during an explosion. As a barricade occupies less ground area than an earth bank, the use of a barricade may become more widespread than the use of an earth bank. Therefore the propagation and attenuation characteristics of blast waves should be investigated in detail, in case the use of a barricade is adopted at ECMs in Japan.

In this study, blast wave pressures were measured by piezoelectric sensors, enabling the effect of a new ECM model on the propagation and attenuation characteristics of blast waves to be investigated quantitatively. One area of concern is the effect of scale, because our experiments were scaled down. There is no doubt that a full-scale experiment carried out in the field would be ideal, but that would be costly and involve a high degree of risk. One way to solve this problem is to conduct experiments at different scales so as to investigate the applicability of the scale law. If the data can be scaled to produce empirical equations, this would be a great help in estimating the blast wave pressure for a full-size magazine.

## 2. Experiments

Table 1 show the experimental conditions. The explosive charge is C-4 with a density of 1400 kg·m$^{-3}$. The explosive in C-4 is RDX, which makes up 91% of its mass, and the remaining 9% is a binder. To obtain standard blast data, a surface detonation of a C-4 charge was conducted in Experiment Number (Ex. No.) 1. The C-4 charge had a cylindrical shape. The height of burst (HOB), representing the distance from the ground surface to the center of the explosive, was set at 0.18 m kg$^{-3}$ in order to avoid forming a crater in the ground.

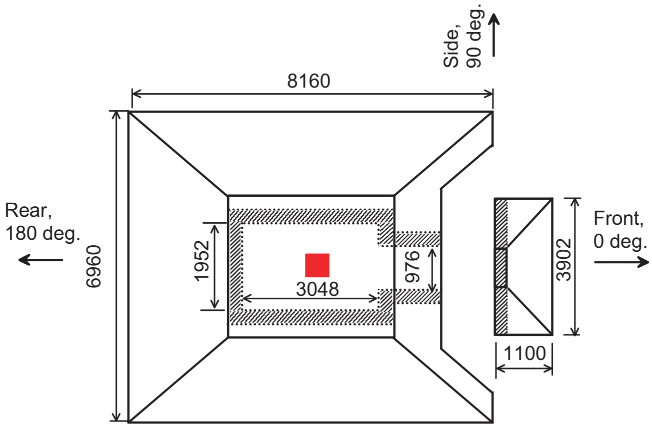
Ex. No.2 was conducted using an ECM. Explosive masses of 160 kg and 20 kg were used in both experiments in order to investigate the scale effect. According to the cube-root scaling law of Hopkinson[10], 160 kg is twice the scale of 20 kg. Cuboid-shaped explosive charges were placed on the bottom of a room in an ECM at the center of an ECM model. The explosive charges were ignited by a 5 g P4 booster charger (PETN/Binder=91/9wt.%), a double-hold detonating fuse and exploding bridge-wire (EBW) detonators (RISI-501).

Figure 1 shows the magazine model, based on an ECM, that was used in Ex. No. 2-1. In this experiment, the ECM was constructed of reinforced concrete with an earth cover. The roof thickness of the ECM was set at 600 mm as a one-fifth scale—considering 3 m for a maximum storage charge of 40 tons. The scale thickness of the roof is constant at 0.11 m·kg$^{-1/3}$. The dimensions of the room inside the ECM were 976 mm in height, 1952 mm in width and 3048 mm in depth. There was a barricade in front of the exit of the ECM. The inner slope of the barricade was

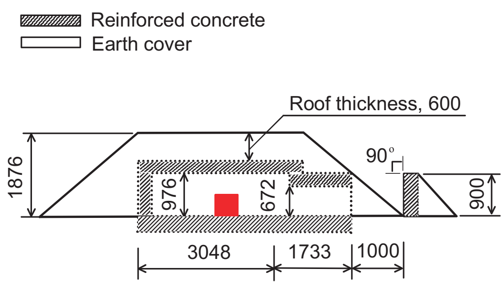
**Table 1** Experimental conditions.

| Ex. No. | Name | Mass, $M$ [kg] | Geometry | M/V* [kg·m$^{-3}$] | Thickness** [m, m·kg$^{-1/3}$] | Note |
|---|---|---|---|---|---|---|
| 1-1 | C-4 | 160 | Cylinder | - | - | Surface burst |
| 1-2 | C-4 | 20 | Cylinder | - | - | Surface burst |
| 2-1 | C-4 | 160 | Cube | 28.1 | 0.6, 0.11 | ECM |
| 2-2 | C-4 | 20 | Cube | 28.1 | 0.3, 0.11 | ECM |

* : Ratio of explosive mass to volume of room in ECM
** : Thickness of earth cover and scaled thickness.




(A) Front view




(B) Side view

**Figure 1** Model of ECM with barricade used in 160 kg test (Unit : mm).

perpendicular to the ground. The barricade was also constructed of reinforced concrete with an earth cover. The distance from the ECM exit to the barricade was set at 1000 mm as the scaled distance at actual scale is the same. The interior dimensions of the ECM used in Ex. No. 2-2 were half those of Ex. No. 2-1. For example, the roof thickness was changed from 600 mm to 300 mm. The ratio (M/V) of the explosive mass to the volume of the room in the ECM was constant as 28.1 kg·m$^{-3}$.

The density and compressive strength of the reinforced concrete were 2150 kg·m$^{-3}$ and 35 MPa, respectively, after 28 days. The mass percent of cement, sand, and water were 20%, 72%, and 8%, respectively. The diameter of rebars and the distances between the rebars were 6.0 mm and 50 mm, respectively, for Ex. No. 2-1, and 2.0 mm and 20 mm, respectively, for Ex. No. 2-2. The density of the earth cover was 1490 kg·m$^{-3}$.

The blast wave pressures were measured using 16 piezoelectric pressure sensors (H102A07 and 102A12, PCB Piezotronics, Inc., Sensitivity : 14.5 and 3.6 mV·kPa$^{-1}$, Resonant Frequency : 250 and 500 kHz). Figure 2 shows the positions of the pressure sensors that were set at four distances in five directions. The front of the ECM is the azimuth angle ($\theta$) of0degree, which is the direction of the extended centerline of the ECM. The distances from the sensors to the ECM exit were 44, 57, 76 and 100 meters at directions of 0, 90, and 180 degrees, and 76 and 100 meter at directions of 45 and 135 degrees. The sensor setup was the same as in a previous study[11].

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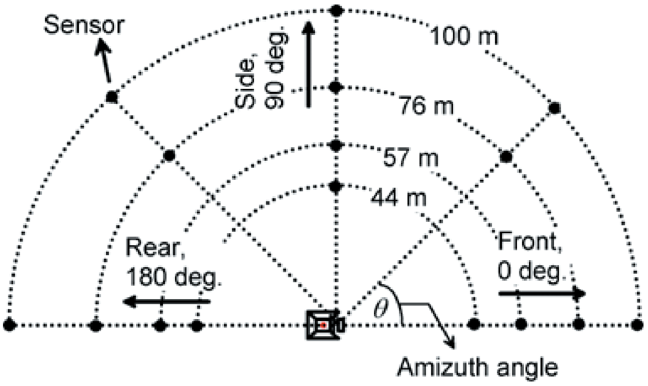



Figure 2 Position of pressure sensors.

The signals were conditioned using pre-amplifiers (480E 09, PCB Piezotronics, Inc.) and recorded on a waveform digitizer (LTT184/8, Labortechnik Tasler GmbH) at a sampling rate of 1.04 MHz and a resolution of 16 bits.

## 3. Results and discussion

Figure 3 shows the time histories of the blast wave pressure at 76 m for Ex. No. 1-1(A) and for Ex. No. 2-1(B, C, D, E and F). The time histories of the blast wave pressure were interpolated by smooth cubic natural spline functions to obtain the blast parameters, which are the peak static overpressure and the positive pressure impulse. It should be noted that the impulse was obtained by the time integral of the overpressure during the positive pressure phase, before the pressure decayed to atmospheric pressure.

### 3.1 Standard blast data for C-4 explosion

Figure 4 show the peak overpressure (A) and scaled impulse (B) of Ex. No. 1 for a burst explosion of a C-4 charge with respect to the scaled distance. The impulse and the distance are scaled by $M$. The obtained data of peak overpressure and scaled impulse were fitted using the following equations :

$$X = \log_{10}(Z) \quad (1)$$

$$\log_{10}(P) = 6.13281 - 2.27251X + 0.35926X^2 \quad (2)$$

$$\log_{10}(I/M^{1/3}) = 2.28471 - 0.61257X - 0.15971X^2 \quad (3)$$

where $Z$ is the scaled distance ($\mathrm{m \cdot kg^{-1/3}}$), $P$ is the peak overpressure (Pa), $I$ is the positive phase impulse (Pa·s),

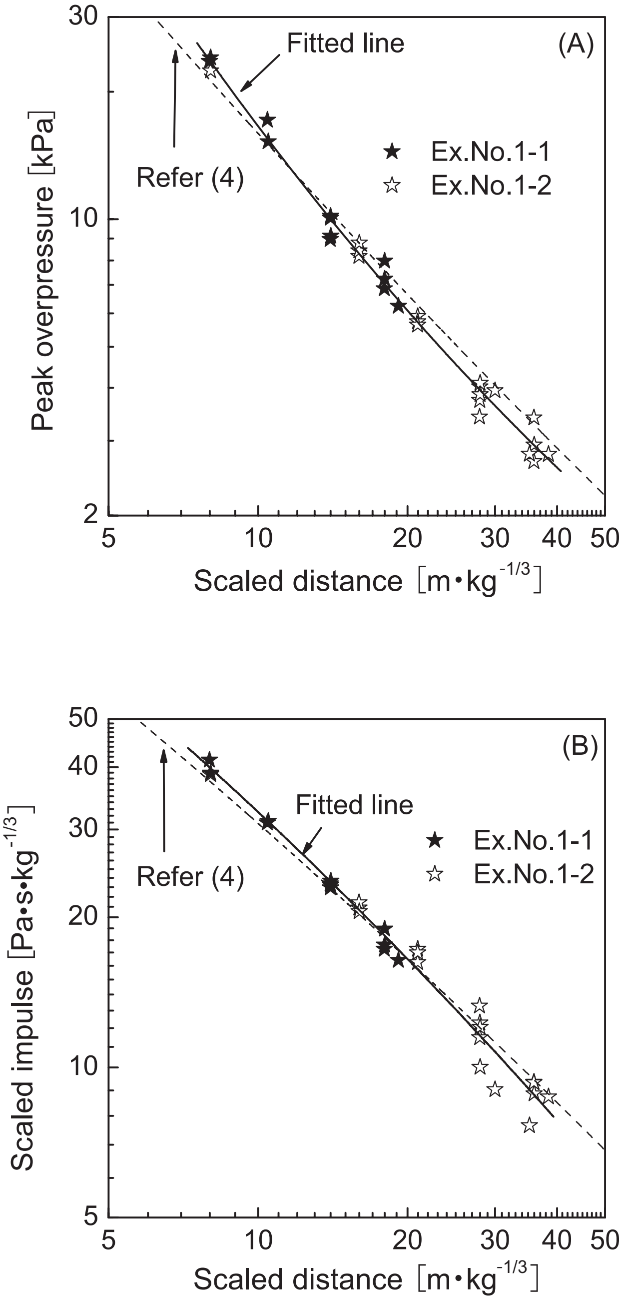



Figure 4 Peak overpressure (A) and scaled impulse (B) of Ex. No. 1 for surface burst with respect to scaled distance.

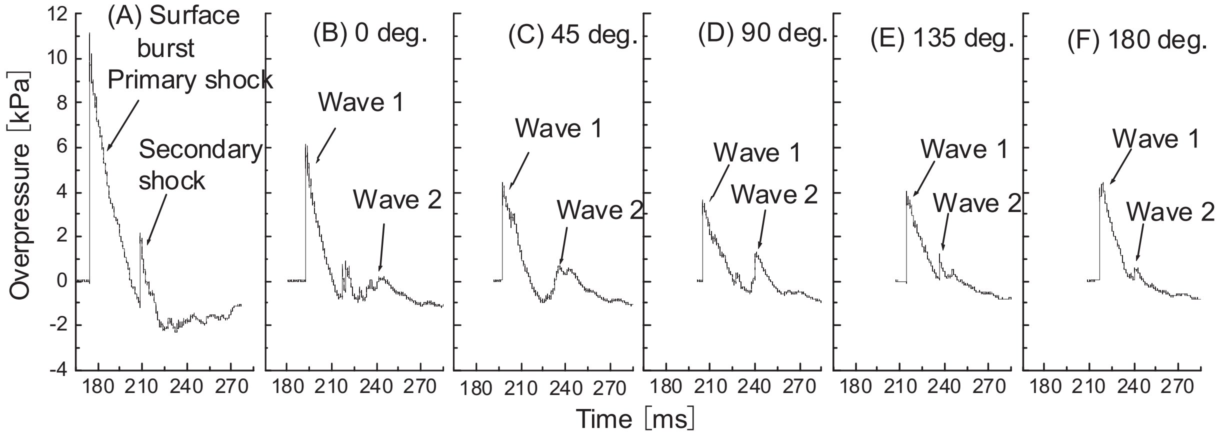


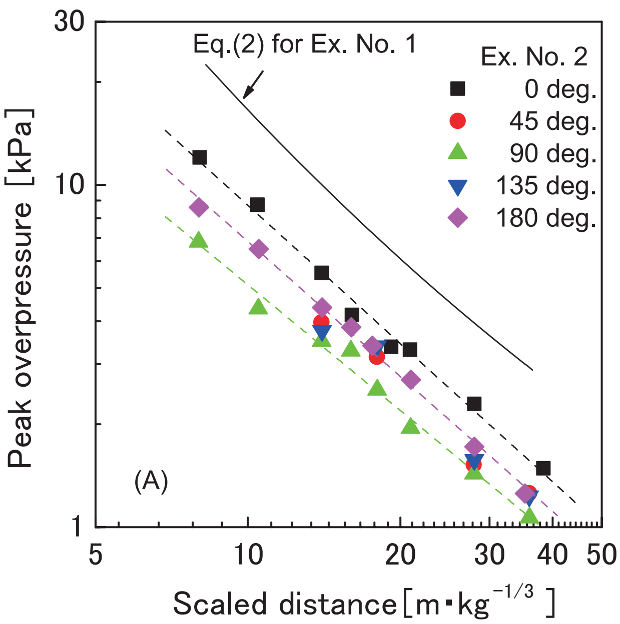

Figure 3 Time histories of blast wave pressure at 76 m for Ex. No. 1-1 (A) and for Ex. No. 2-1 (B, C, D, E, F).

and $M$ is the mass of the C-4 charge (kg).

To confirm the validity of this experiment, the previous experiment results[12] are shown as a dashed line in the figure. As both results are in good agreement, the reproducibility of this experiment is confirmed and standard data for comparing with the data for ECM are obtained.

### 3.2 Attenuation and propagation characteristics of blast wave pressure for ECM

Figure 5 shows the peak overpressure and the scaled impulse for the ECM in Ex. No. 2 with respect to the scaled distance. The data for the ECM decreased significantly, so that both peak overpressure and the impulse were markedly lower than those for the surface burst in Ex. No. 1. One of the reasons for this is thought to be that some energy from the explosion was converted into the kinetic energy of the fragments and the destruction of the reinforced concrete and earth cover. We confirmed that the ECM was destroyed completely by the explosion of the C-4 charge. The figures also show that the data for each azimuth angle are different, in spite of the same scaled distance. Thus it is clear that there is some directionality of blast wave propagation until 40 $m \cdot kg^{-1/3}$.



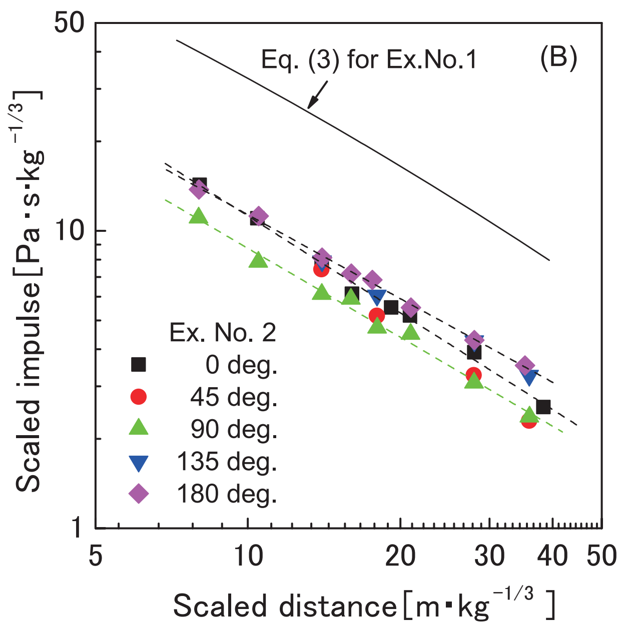




**Figure 5** Peak overpressure (A) and scaled impulse (B) for ECM of Ex. No. 2 with respect to scaled distance.

**Table 2** Empirical constants for estimation of blast wave pressure from ECM.

| Angle | Peak pressure | | Impulse | |
|---|---|---|---|---|
| $\theta$ | A | B | A | B |
| 0deg. | 5.282 | -1.342 | 2.132 | -1.082 |
| 90 deg. | 4.929 | -1.221 | 1.936 | -0.995 |
| 180 deg. | 5.144 | -1.309 | 1.990 | -0.936 |

In order to investigate the attenuation characteristics for each azimuth angle, the dashed lines show a logarithmic relationship between the peak overpressure and scaled distance. The dashed lines were fitted by a simple polynomial regression of A+B·X, where A and B are empirical constants, as shown in Table 2, and X is calculated by using Eq. (1). An interesting point in Figure 4 and Table 2 is that the lowest values do not occur at the rear of the structure, but at the side of 90 degrees.

To confirm the validity of these experimental results, the experimental results of Aibano[8] for an ECM are investigated in detail. In the Aibano experiment, the explosive and the roof thickness were a dynamite charge of 250 kg and 3.0 m, respectively, meaning the scaled roof thickness was 0.48 $m \cdot kg^{-1/3}$, and the M/V was 17.5 $kg \cdot m^{-3}$. The structure of the barricade and the M/V are similar to those in the experiment reported here. One difference is that the roof thickness was four times thicker than that in this experiment. In comparison with the data, the distance are scaled using dynamite mass because the explosion energies of dynamite and C-4 are not so different[9), 13)]. In the Aibano experiment, the peak overpressure for the three directions of the front, the side and the rear was measured using a blast meter. The result of the previous experiment[8] shows that the highest value of peak overpressure appeared at the front, and the lowest values occur at the side, which are the same as the result of this experiment. Furthermore, it is considered that the effects of the roof thickness of 0.11 $m \cdot kg^{-1/3}$ and 0.48 $m \cdot kg^{-1/3}$ on directionality are similar qualitatively.

To investigate the reason the lowest values occur at the side of 90 degrees, the time histories of the blast wave pressure were compared. As already shown in Figure 2, the time histories of the blast wave pressure at 76 m for Ex. No. 1-1(A) and for Ex. No. 2-1(B, C, D, E and F) were investigated in detail. Figure 2(A) shows clearly that a secondary shock is caused by the implosion of a rarefaction wave from the contact surface between the explosion products and the air. However, it is difficult to confirm the secondary shock in the time histories of Figure 2(B)-(F) for Ex. No. 2-1. In Figure 2(B)-(F), Wave1 represent the primary shock wave, and Wave 2 is

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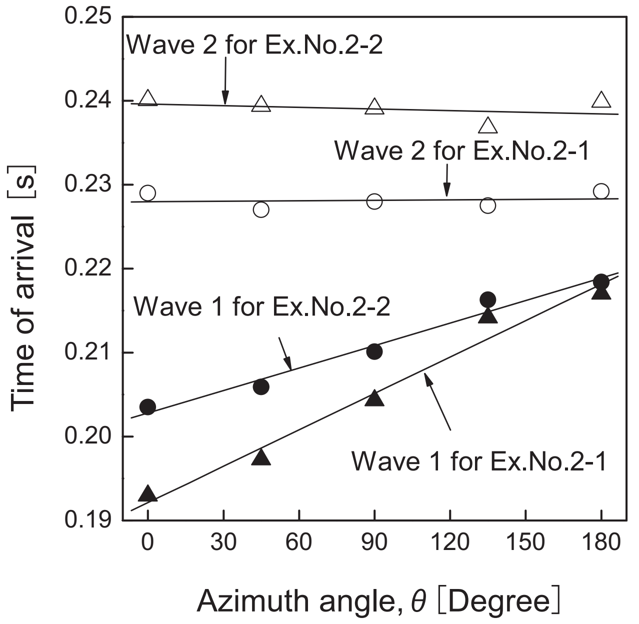


**Figure 6** Time of arrival of Wave1and Wave 2 at 76 m for Ex. No. 2-1 and 2-2.

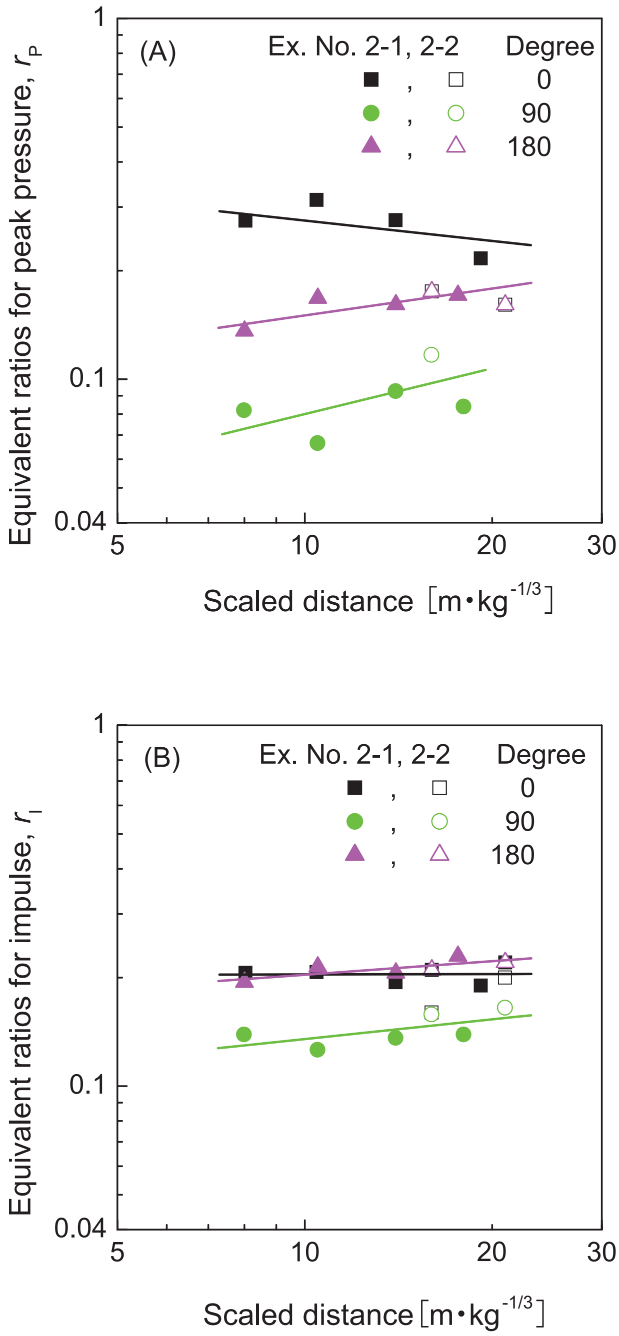


**Figure 7** Equivalent weight ratios by peak overpressure (A) and impulse (B).

confirmed when the arrival time of peak overpressure is approximately 240 ms. In addition, before Wave1decays to atmospheric pressure, Wave 2 arrives. In order to understand the propagation characteristics, Figure 6 shows the arrival times of Wave 1 and Wave 2 at 76 m in Ex. No. 2-1. It is found that the arrival time of Wave 1 increases with the increase in the azimuth angle. This tendency is similar to the result of a previous study for an UGM that is not destroyed by an explosion inside the magazine[4]. It is considered that Wave1arrives due to the diffraction of the blast wave from the exit of the ECM and the reflection from the barricade. Wave1should converge and interfere at the rear of the ECM because this model is symmetrical with respect to the center axis of the exit. This is the reason the lowest values of the blast parameters do not occur at the rear of the ECM. In contrast, the arrival times of Wave 2 are almost constant in spite of the different azimuth angle. It is considered that Wave 2 linearly propagates from the center of the room in the ECM, that is the explosive position, after the ECM was destroyed.

### 3.3 Applicability of scaling law with equivalent weight

In order to investigate the scale effect for blast wave pressure, the scaled distance ($Z_{equ}$) that has the same values of peak overpressure of Ex. No. 2 was obtained from Eqs. (1)-(2).Therefore, the equivalent weight ($M_{equ}$) and equivalent weight ratio for peak overpressure ($r_P$.) were calculated by Eq. (4).

$$r_P = \frac{M_{equ}}{M} = \left(\frac{Z}{Z_{equ}}\right)^3_{P=constant} \tag{4}$$

The equivalent weight ratio for impulse ($r_I$) was calculated in the same way. The results for each scaled distance are shown as equivalent weight ratios ($r_P$, $r_I$) in Figure 7. The average values for $r_P$ at scaled distances of 7-23 m·kg$^{-1/3}$ are about 0.26 for the front, about 0.08 for the side and about 0.16 for the rear, and the averages $r_I$ are 0.26 for both the front and side, and 0.13 for the rear.

The data for $r_P$ and $r_I$ are fitted by a straight line. The fitted lines show clearly that the $r_P$ values with respect to scaled distance are not constant but vary. Although the fitted lines depend on the azimuth angle, the fitted lines approximate a certain value with the increase in scaled distance. This means that although there is some directionality near the magazine, it will disappear at distance due to the diffraction of the blast wave. It is considered that the fitted lines adequately represent the propagation characteristic of blast wave. At the same time, although the data are few, the results for the different scale experiments of Ex. No.1and No. 2 approximately correspond with certain fitted lines. In other words, provided the scaled distance and the same azimuth angles, $r_P$ and $r_I$ are the same. Based on these results, it is considered that the blast wave pressure from the explosion inside an ECM can be estimated by the cubic-root scaling law.

This study focused on propagation and the attenuation characteristics of blast wave pressure with the aim of improving the safety of ECMs. Further study is required to investigate the behavior of the fragments that are generated by the destruction of reinforced concrete and the earth cover for highly reliable safety for ECMs.

## 4. Conclusions

The attenuation and propagation characteristics of a blast wave resulting from an explosion inside an earth-covered magazine (ECM) with a scaled roof thickness of $0.11\,m\cdot kg^{-1/3}$ were investigated. The inner slope of a barricade positioned in front of the model ECM was perpendicular to the ground surface. Our conclusions are :

1. The blast wave pressure from the explosion inside the ECM decreased significantly, so that both the peak overpressure and the impulse were markedly lower than those for a surface detonation. One of the reasons for this is thought to be that some energy from the explosion was converted into the kinetic energy of the fragments and the destruction of the reinforced concrete and earth cover.
2. There is some directionality of blast wave propagation until $40\,m\cdot kg^{-1/3}$. The directionality shows that the highest values appear at the front of the ECM and the lowest values occur at the side. The average values of equivalent weight ratio for peak overpressure were approximately 0.26 for the front, 0.08 for the side and 0.16 for the rear. The average values for impulse were approximately 0.21 for both the front and side, and 0.13 for the rear. The main reason for this is considered to be that blast wave pressures from the exit of the ECM propagate and arrive at the rear of the ECM due to the diffraction of the blast wave and reflection by the barricade.
3. The results of different scale experiments obtained using a small ECM model show that it is possible to estimate the blast wave pressure resulting from an explosion inside an ECM by using the cubic-root scaling law provided the scaled distance and the azimuth angle are scaled the same.

These experimental results are worth taking into consideration in order to design magazines with a higher degree of safety.

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