Letter

Water and sand for blast pressure mitigation around a subsurface magazine

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Abstract

A subsurface magazine has a chamber underground with a passage vertical to the ground surface. A pentaerythritol tetranitrate (PETN) pellet of 1.00 g was detonated in a subsurface magazine model to evaluate the blast peak overpressure and the positive impulse around the subsurface magazine. The presence of water or sand in the chamber mitigates the blast peak overpressure and positive impulse remarkably. Precise data obtained from the experiments are presented herein.

Keywords : subsurface magazine, blast wave, mitigation, water, sand

1. Introduction

A subsurface magazine has an underground explosive storage chamber, a horizontal passageway, and a vertical shaft for the entrance. Residential buildings are increasingly located near magazines. In fact, maintaining such structures at a safety distance is becoming increasingly difficult. Subsurface magazines were proposed recently in Japan to reduce the effects of blast waves, fragments, and ground shock and to maintain a safety distance easily when storing explosives underground. Therefore, blast pressure evaluation of the area around a subsurface magazine is important.

Blast pressure around a subsurface magazine has been described in several reports.[1)-5)] Some water accidentally entered the chamber of the subsurface magazine model in one large-scale field experiment[5)]. The blast pressure around the magazine of the experiment was thereby remarkably reduced. The reproducibility of that finding must be examined because the result is useful and important for application.

Therefore, this study examined the effect of water on the storage chamber of the subsurface magazine to the blast pressure. Even if the mitigation effect of water is confirmed, it should be unsuitable to introduce water into the explosive storage chamber from the standpoint of safety. Therefore, the mitigation effects of sand were also evaluated. Small-scale indoor experiments were conducted to confirm the reproducibility of the mitigation effect.

2. Experimental

2.1 Test explosives

A pressed pellet made of pentaerythritol tetranitrate (PETN) and carbon powder was used as an explosive. The pellet consists of 95 wt.% of PETN and 5 wt.% of carbon powder. The cylindrical pellet was 7.5 mm long with 7.5 mm diameter. The pellet weight and the density were, respectively, 0.50 g and 1.55 $\mathrm{Mg \cdot m^{-3}}$. Two pellets of 0.50 g were glued together to form a long cylinder used as a 1.00 g pellet. The Hopkinson-scaled distance (*scaled distance*) and the Hopkinson-scaled positive impulse (*scaled impulse*) were obtained using the distance or positive impulse divided by the cube root of the net weight of PETN, 95%

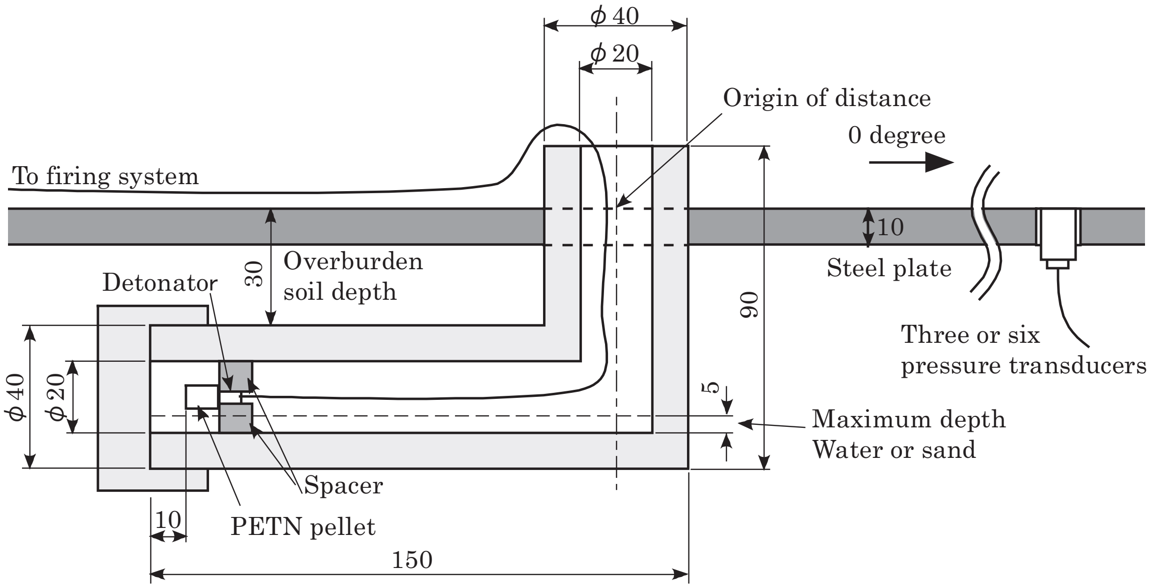

Figure 1 Schematic diagram of subsurface magazine model in this study. The length is shown in millimeters.

of the measured weight of the pellets. A specially designed electric detonator with 100 mg lead azide was used. The detonator was glued onto the top of the pellet. Showa Kinzoku Kogyo Co., Ltd. supplied the explosives and detonators. Then 4 kV was applied to initiate the detonator using a firing system (FS-43 ; Teledyne RISI, Inc.).

Six surface explosion experiments were conducted for comparison. The pellet of 0.50 g or 1.00 g was put on a cardboard cube, placed on the ground-surface model, described later, and detonated. A cubic spacer was used to adjust the height of the explosive center to $0.18\,\mathrm{m{\cdot}kg^{-1/3}}$. The spacer was made of pasteboard.

2.2 Subsurface magazine model

The model is presented in Figure 1. The model was basically designed by referring the model for the previous field experiments[5]. The subsurface magazine model was made of a steel pipe. The interior diameter was constant throughout the model, including not only the passageway but also the shaft. This model did not particularly separate the storage chamber and the passageway. The shaft was welded perpendicularly to the storage chamber. The shaft was fixed perpendicularly to a ground-surface model, as described later, using bolts and nuts. The pellet was placed on the central axis of the storage chamber. The distance from the innermost wall to the pellet base was set as 10 mm. Tap water or sand (apparent density of $2.3\,\mathrm{Mg{\cdot}m^{-3}}$) of $6.0\times10^{-6}\,\mathrm{m^3}$ ($6\,\mathrm{cm^3}$) or $9.0\times10^{-6}\,\mathrm{m^3}$ ($9\,\mathrm{cm^3}$) was put into the model magazine to assess the effects of water and sand. The maximum depth of the water and sand was 5 mm for $9\,\mathrm{cm^3}$. The explosive did not contact the water or sand at all. The numbers of experiments was tabulated in Table 1. The overburden soil depth, defined by the distance from the outer surface of the chamber wall to ground level[4], was 30 mm. However, the space in this model was filled with air, not soil.

Table 1 Numbers of experiments in this study.

Condition	Number of experiments
Surface explosion	6
Subsurface magazine (SM)	5
SM with $6\,\mathrm{cm^3}$ sand	1
SM with $9\,\mathrm{cm^3}$ sand	2
SM with $6\,\mathrm{cm^3}$ water	3
SM with $9\,\mathrm{cm^3}$ water	5

2.3 Ground-surface model and blast pressure measurement

A steel plate with respective length, width, and thickness of 3200 mm, 2000 mm, and 10 mm, was fixed on a table. This plate was regarded as a ground-surface model. The plate was replaced with a 2200-mm-wide plate in the latter part of the experiments.

Three or six pressure transducers (102M256 ; PCB Piezotronics, Inc.) were used to measure the blast pressure. The pressure transducers were set with the vibration isolator (GEL Tape ; Taica Corp.) because the transducer diaphragm was flush with the ground surface model. The distance from the center of the explosive (surface explosion) or the shaft center (subsurface magazine model) was 800 mm, 1200 mm, and 1600 mm in the case of three transducers, or 400 mm, 600 mm, 750 mm, 1200 mm, 1800 mm, and 2400 mm in the case of six transducers. Figure 1 shows that the transducers were placed in a line on the opposite side to the storage chamber. The corresponding scaled distance was $4.1\,\mathrm{m{\cdot}kg^{-1/3}}-24.4\,\mathrm{m{\cdot}kg^{-1/3}}$. The output signals were recorded using a transient recorder (LTT184/8, sampling rate of 1.04 MHz and resolution of 16 bits in this study ; Labortechnik Tasler GmbH) through an amplifier system (30510 and 30622 ; H-Tech Laboratories, Inc.).

3. Results and discussion

The subsurface magazine model and the surface model were not destroyed or deformed in this study. The blast

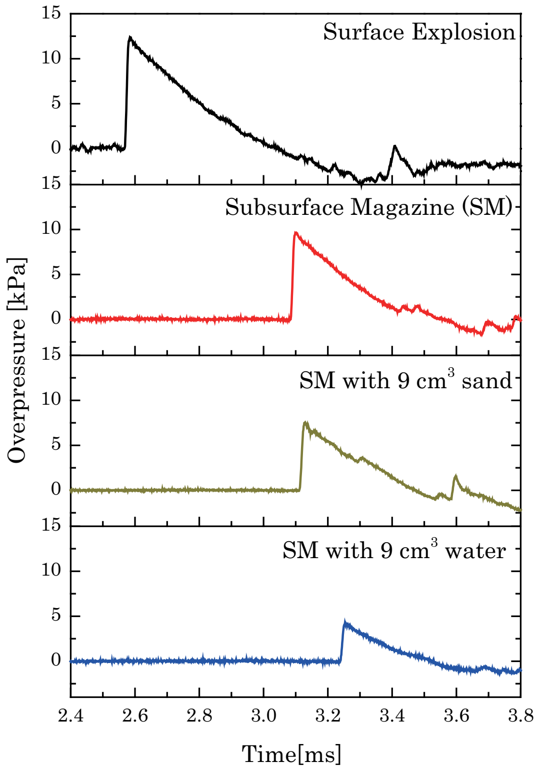

Figure 2 The representative pressure histories of this study. The profiles were obtained at the point whose distance from the center of the explosive (surface explosion) or the shaft center of the subsurface magazine model was 1200 mm, corresponding scaled distance was 12.2 m·kg$^{-1/3}$. Time zero is the timing of sending a trigger signal to the firing system.

wave emerged only from the shaft opening. In contrast, blowup of soil immediately above the storage chamber was observed in field experiments[5]. Therefore, the model in this study simulated the most dangerous conditions with respect to blast waves.

Figure 2 shows the representative pressure history, obtained at the distance of 1200 mm, corresponding scaled distance of 12.2 m·kg$^{-1/3}$. Time zero is the timing of sending the trigger signal to the firing system. The wave profiles for the explosion in the subsurface magazine were almost similar to those for the surface explosion. The blast wave arrival and the peak pressure for the explosion in the subsurface magazine were late and small, respectively, compared with those for the surface explosion. This tendency was enhanced, when sand or water was in the storage chamber.

The obtained pressure history was fitted using a spline function. Then, the peak overpressure and scaled impulse were determined. The relation between the peak overpressure, the scaled impulse, and the scaled distance are presented in Figures 3(a) and 3(b). The representative data of the surface explosion of TNT, named MITI87[6, 7], was also represented as a broken line. As the MITI87 is the data set of the surface explosion ranging from scaled distance of 2 m·kg$^{-1/3}$ to 20 m·kg$^{-1/3}$, MITI87 was represented only in this range in Figures 3(a) and 3(b). The height of the explosive center of MITI87 experiments[6, 7] was set to be 0.18 m·kg$^{-1/3}$.

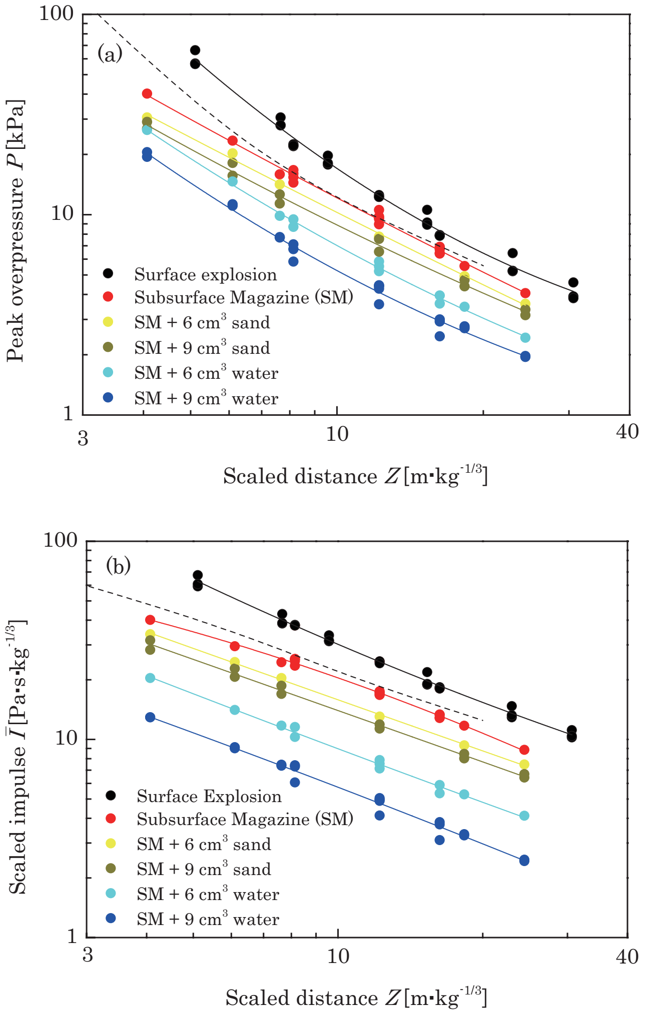

Figure 3 Relation between the scaled distance and (a) the peak overpressure and (b) the positive scaled impulse. The solid lines are fitted curves, and the broken line is the data of MITI87[6, 7].

The peak overpressure and the scaled impulse decrease with the scaled distance for all experimental condition. This result is in accordance with the previously published surface explosion data, for example, MITI87[6, 7]. Figure 3 shows that the surface explosion data of this study are larger than those of MITI87, represented as the broken line in Figure 3, compared at the same scaled distance. This fact demonstrates that the test explosives used in this study detonated completely. One of the reasons of the difference is that the TNT equivalent ratio of PETN was more than one[8]. In addition, MITI87 is the data set of experiments carried out on the open-air field, thus the reflection on the ground surface reduced the blast wave compared with the steel plate in this study.

Both peak overpressure and scaled impulse data of the subsurface magazine are small compared those of surface explosion at the same scaled distance. This result proves the mitigation effect of the subsurface magazine. In addition, the values are smaller in order of 6 cm^3 sand > 9 cm^3 sand > 6 cm^3 water > 9 cm^3 water. These experimental results substantiate that sand or water in the storage chamber cause the mitigation effect for blast pressure reproducibly. The mitigation effect of water is

Table 2 Fitting parameters of quadratics as a log − log plot for the relation between the blast parameters and the scaled distance.

	Peak overpressure			Scaled positive impulse		
	a	b	c	l	m	n
Surface explosion	0.77514	−3.18900	3.64481	0.19187	−1.41627	2.70444
Subsurface magazine (SM)	0.11416	−1.29565	2.46551	−0.26065	−0.32876	1.89997
SM with 6 cm^3 sand	0.06772	−1.35640	2.30021	0.00854	−0.87644	2.06779
SM with 9 cm^3 sand	0.20943	−1.61347	2.35289	−0.00484	−0.84970	2.00021
SM with 6 cm^3 water	0.39127	−2.10631	2.56131	0.03897	−0.98785	1.90181
SM with 9 cm^3 water	0.50923	−2.31797	2.52989	−0.06214	−0.80654	1.62734

larger than that of sand and the mitigation effect increases with the amount of water or sand in the range of this study.

The relation between these blast parameters 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 a, b, c, l, m, and n of the following equations.

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

$$\log_{10} P = aX^2 + bX + c \qquad (2),$$

$$\log_{10} \overline{I} = lX^2 + mX + n \qquad (3).$$

In those equations, Z stands for the scaled distance ($m \cdot kg^{-1/3}$), P represents the peak overpressure (kPa), and $\overline{I}$ denotes the scaled impulse ($Pa \cdot s \cdot kg^{-1/3}$). Table 2 presents the fitting parameters obtained in the present study. The fitted curves are also shown in Figures 3(a) and 3(b).

The water and sand in the subsurface magazine was found to mitigate the blast pressure. In the previous papers, the mitigation of blast waves using barrier materials, such as saw dust[9)] and water gel[10),11)], have been reported extensively. The explosives in these papers were completely covered by the barrier materials and the blast wave surely propagated into the barrier materials. The mitigation mechanisms are explained to be caused by the compression of the porous materials by the blast wave[9)], or the multi reflections in the barrier materials[11)]. On the contrary, as the explosive was not contact with water or sand in this study, the blast wave propagated across the water or sand layer. Thus, the mitigation mechanisms should be different and they have not been discussed as far as the authors know. Although the interaction between a shock wave and a water layer when the shock wave propagate across the water layer has been discussed in the other paper[12)], the mitigation of the shock wave was not described.

The mitigation mechanisms remain as a subject for future investigation. At this moment, the mitigation mechanisms are expected to be the following : conversion from the energy of blast wave to kinetic and internal energies of water or sand, followed by absorption by evaporation of water or the fragmentation of water or sand. Reflection of the blast wave at the water or sand surface is expected to reduce to a greater degree than by a solid surface such as steel. However, the contributions of these factors to the mitigation effect is not clear.

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