Research paper

Experimental studies on debris hazards from explosions in subsurface magazines

Tei Saburi*†, Shiro Kubota*, Katsumi Katoh**, and Yuji Ogata*

*Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology (AIST), Onogawa 16–1, Tsukuba, Ibaraki 305–8561, JAPAN
Phone : +81–29–861–8760
† Corresponding address : t.saburi@aist.go.jp

**Department of Chemical Engineering, Faculty of Engineering, Fukuoka University, 8–19–1 Nanakuma, Jonan–ku, Fukuoka 814–0180, JAPAN

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Abstract

Accidental explosions in explosive facilities such as explosive magazines cause the ejection of hazardous fragments and debris as well as create airblast overpressure. Subsurface magazines are promising for mitigating these hazards and reducing the quantity-distance (QD) criteria. A subsurface magazine is constructed in the ground to mitigate the explosive hazard, and is equipped with a storage chamber, an access tunnel, and a vertical shaft used as an exit. From the viewpoint of safety assessment, it is important to evaluate the safe distance from hazardous fragments and debris associated with an explosion in a subsurface magazine. In this study, the debris produced by explosions in subsurface magazines was experimentally evaluated. Box-shaped (flat roof) and arch-shaped scale-model magazines were prepared, and scaled internal explosion tests using Composition C4 explosive were conducted at predetermined loading densities. The relationships of debris quantity–distance, mass–distance, and so on were evaluated in order to establish the suitable siting and design of explosive facilities. The results are expected to contribute to the establishment of QD regulations for the debris hazards of subsurface magazines.

Keywords : explosions, fragments and debris, subsurface magazine

1. Introduction

Three types of permanent explosive storage magazine are now regulated by Explosives Control Act in Japan : above-ground magazines, earth-covered (igloo type) magazines, and underground magazines. However, cases of construction in limited spaces have recently increased. It is necessary to develop a new type of magazine that can reduce the separation distances from inhabited buildings, public traffic routes, and other magazines. Subsurface magazines have been proposed as a suitable type of magazine. A subsurface magazine is constructed in the ground to mitigate the explosive hazard, and a vertical elevator is used as an exit from the storage chamber. To establish safety standards and design criteria for subsurface magazines, as with other types of magazine[1)–3)], the effects of the debris from an accidental explosion in the magazine should be evaluated as well as the effects of the air blast pressure. Although there have been reports on the air blast properties due to such factors as the moisture content in the soil[4)], the storage structures[5)], and the explosive loading density[6)], there have been few reports on the properties of debris.

In this study, scale-model magazines equipped with a vertical transport shaft were constructed underground, and scaled explosion tests using Composition C4 explosive were conducted to acquire data on the debris caused by accidental explosions. Two types of subsurface magazine with box-shaped and arch-shaped storage chamber, were constructed and tested. The effects of changing the chamber loading density were evaluated for the arch-shaped chamber. The behaviors of the explosions in the tests were observed using a high-speed video camera. The

Table 1 Test cases.

	No.1-1	No.1-2	No.1-3
Explosive charge quantity [kg]	12.85	3.43	11.8
Storage chamber volume [m^3]	2.57	1.14	2.36
Chamber loading density quantity of explosive per unit volume [$kg \cdot m^{-3}$]	5	3	5
Standoff from floor to center of explosive [cm]	8.6	10.7	19.6
Chamber structure shape	Arch	Arch	Box
Chamber internal width [m]	1.5	1.0	1.2
Chamber internal height [m]	1.05	0.7	1.0
Chamber internal length [m]	2.0	2.0	2.0
Chamber cover depth (thickness of soil between chamber ceiling and ground surface) [m]	0.69	0.44	0.67
Scaled chamber cover depth [$m \cdot kg^{-1/3}$]	0.29	0.29	0.29

distributions of the number and mass of debris resulting from the explosions were measured and their dependences on the scaled distance were evaluated.

2. Experiment

To investigate the effects of differences in the magazine storage structure and chamber loading density, three denoted No. 1-1 to 1-3 were conducted as shown in Table 1. Two types of magazine structure were prepared. One had a box-shaped chamber, and the other had an arch-shaped chamber. The effects of the difference in structure were examined by comparing the results of No. 1-1 and 1-3. The effects of the chamber loading density were also examined for the arch-shaped chamber, by comparing the results of No. 1-1 and 1-2.

2.1 Explosive

Composition C-4 explosive was used in the experiments. Explosive charges were housed in a wooden box in No. 1-1 and 1-3, and were arranged in a sphere in No. 1-2. Explosive charge quantity was based on a given chamber loading density, which is 5 $kg \cdot m^{-3}$ in No. 1-1 and 1-3, and 3 $kg \cdot m^{-3}$ in No. 1-2, and all charges were located in the center of the chamber at a certain standoff from the floor as shown in Table 1.

The C-4 charges were initiated with a double-fold detonating fuse and two exploding bridge wire (EBW) detonators. The total length of the detonating fuse was 16 m in No. 1-1 and 1-3, and 14 m in No. 1-2.

2.2 Scale-Model magazines

Schematic diagrams of the subsurface magazines are shown in Figure 1. The magazines were mainly composed of a storage chamber, a magazine tunnel, and an elevator shaft. The chambers were modeled with box-shaped and arch-shaped precast concrete culverts. The internal dimensions of the chambers are shown in Table 1. The chamber cover depth is also shown in Table 1, and it gives a scaled cover depth of 0.29 $m \cdot kg^{-1/3}$. The other components such as the tunnel, elevator shaft, and other boundary walls were made of precast reinforced concrete (JIS A 5372/5371), in which D10 SD295 reinforcing bars were longitudinally and laterally arranged at intervals of approximately 20 cm. D13 SD295 rebars were used at the elevator shaft corners. The most common thickness of the concrete components was 67 mm. The internal dimensions of the magazine tunnels and elevator shafts were 540×540×1273 and 540×540×2293 mm, respectively. The dimensions of boundary slab walls A, B, and C were 1700×1300, 674×900, and 500×1300 mm, respectively. Photograph of the underground installation of the model magazines are shown in Figure 2.

2.3 Measurements

Test shoots of explosion of the magazines were observed using a Photron FASTCAM SA5 high-speed video camera at a 1000 fps frame rate with 1024×1024 pixel image resolution. The focal length and aperture of the lens were 200 mm F5.6 (No.1-1) and 200 mm F2.8 (No.1-3), respectively, and the recording position was about 100-150 m away from the explosion source point. After the explosions, debris projected from the explosion in the magazine was recovered. Every piece of debris with a mass exceeding 20 g was measured and X and Y positions were recorded with reference to an X-axis and Y-axis as shown in Figure 3. The origin is on the ground surface above explosion source point in the chamber buried in the ground. The areal distribution of the debris, the number of fragments–distance and weight–distance relationships, and the cumulative mass distribution were evaluated.

3. Results and discussion

Figure 4 shows high-speed video images of explosions of the arch-shaped (No.1-1) and box-shaped (No.1-3) structures. In No. 1-1, a flame protruding from the vertical shaft exit could be seen 3 ms after ignition, and the flame continued to blaze up spherically. The ground surface started to rise 22 ms after the ignition, and the elevation of the ground around the slab wall increased. On the other hand, in No. 1-3, although a flame protruding from the exit was observed 1 ms after ignition, the flame disappeared immediately. This may have been caused by the existence of trapped water in the chamber due to moisture in the soil. The elevation of the ground surface started to increase 9 ms after the ignition.

There are two types of fragment projected from explosions depending on their origin[3),7)]. The first type of fragment is referred to as primary fragments, which result from the shattering of materials in direct contact with the explosives. These fragments are small and travel at thousands of meters per second. The second type of fragment is referred to as secondary debris. These fragments are larger than primary fragments and travel at several hundred meters per second. Because subsurface magazines are buried underground, secondary debris is considered to be the dominant type of fragment because of

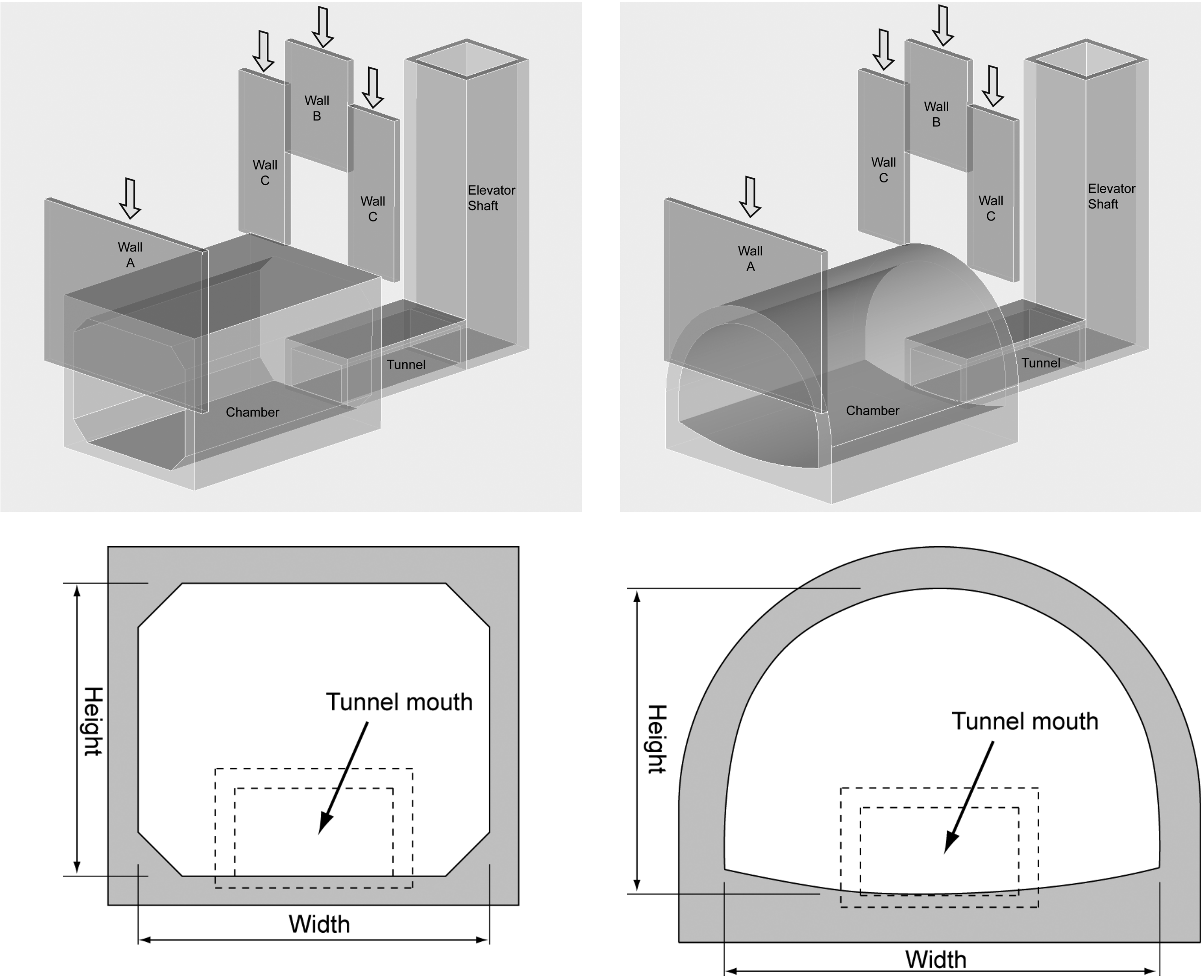

Figure 1 Schematic drawings of the box−shaped (left) and arch−shaped (right) storage chambers with culvert structures.

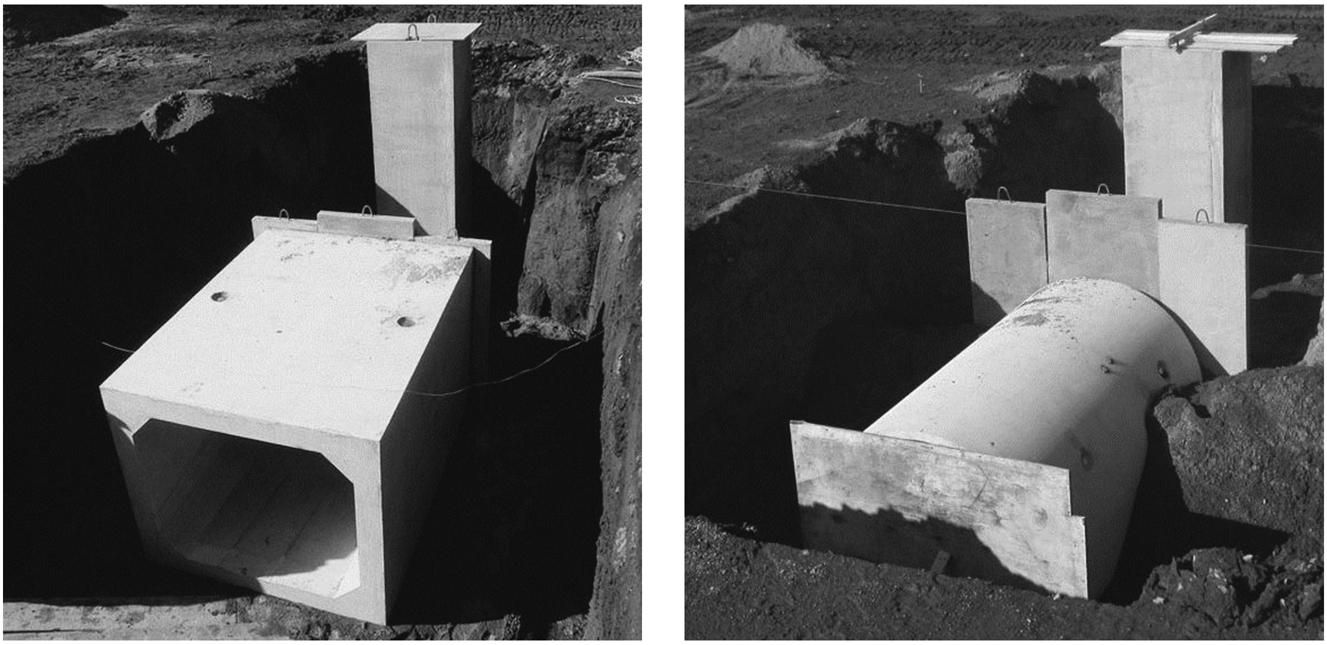

Figure 2 Photographs of the construction of the box−shaped (left) and arch−shaped (right) storage chambers with culvert structures.

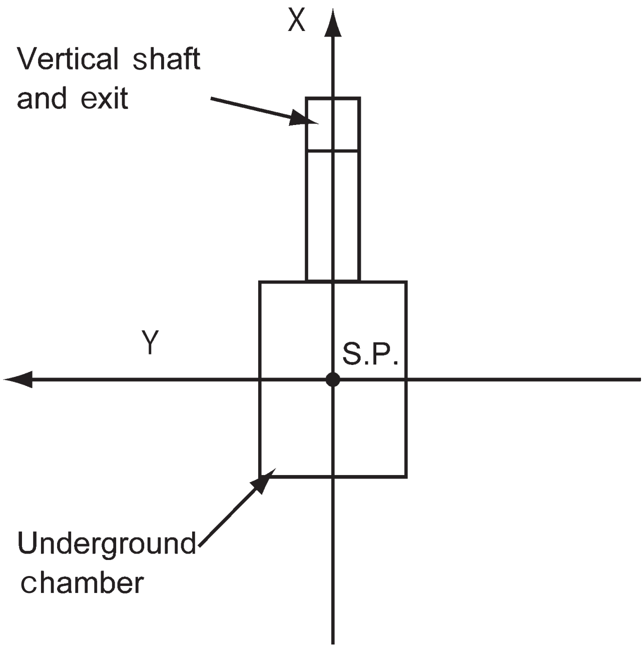

Figure 3 Coordinates used in debris recovery.

soil covering the subsurface magazines. The spatial distributions of the number and mass of fragments resulting from the explosions were measured and are summarized in Figure 5. Throughout the test cases, the spatial center position of distribution has a tendency to be situated slightly on the x direction. There are two main sources of debris: debris caused by the overburden rupture of the chamber and debris caused by the failure materials through the vertical shaft portal. The tendency is attributed to the existence of the vertical shaft portal. The longest distances of the fragments from the explosion source were 33.0 m (400 g) for No. 1-1, 30.6 m (136 g) for No. 1-2, and 27.0 m (30 g) for No. 1-3. The total numbers, gross weights, and average weights of the collected fragments were 873 pieces, 304 kg, and 349 g for No. 1-1, 117 pieces, 69 kg, and 590 g for No. 1-2, and 1017 pieces, 317 kg, and 312 g for No. 1-3, respectively. The DDESB defines a hazardous fragment density as a density exceeding one fragment per 600 sq.ft. (56.7 m^2)[3]. A hazardous fragment is defined as one having an impact energy of 58 ft-lb (79 J) or greater. In this study, all recovered debris was treated as a hazardous fragment. On the right side in Figure 5, the densities of hazardous debris for each explosion are shown in terms of scaled distance. Each item of debris is within the scaled distance corresponding K16 in the Japanese QD criteria. However, it is not easy to relate the debris hazard to the scaled distance.

Comparing the fragments for the two types of chamber structure at the same loading density of 5 $kg{\cdot}m^{-3}$, there were no significant differences in the total numbers and gross and average weights of fragments between the box-shaped and arch-shaped chamber structures. However, the tendency that heavier fragments in No. 1-1 were scattered a short distance than those in No. 1-3 can be seen as shown in Figure 6. Comparing the fragments at the different chamber loading densities for the two arch-shaped structures, the total number and gross weight of fragments collected for No. 1-2 were clearly smaller than those collected for No. 1-1. But it requires consideration of the difference between them in absolute amount of explosive as well as the loading density.

In Figure 7, debris mass distribution is described using a normalized cumulative number of debris $N(m)$ and a normalized cumulative debris mass $M(m)$[8]. $N(m)$ denotes the normalized total number of fragments with the mass greater than m, and $M(m)$ denotes the normalized total mass of all fragments with individual mass greater than m. As for $N(m)$ in No. 1-1 and 1-3, the distribution can be described with a expression: $N(m) = A{\cdot}\exp(-B{\cdot}m^{1/2})$. By means of curve fitting, coefficients A and B were 1.024 and 0.0773 for No.1-1 and 1.0132 and 0.0841 for No. 1-3, respectively. $N(m)$ and $M(m)$ in No. 1-2 doesn't show the same tendency with that in No. 1-1 and 1-3. This is due to the existence of some heavy fragments with a mass exceeding 10 kg and the shortage of the total numbers of fragments in No. 1-2, because the absolute amount of explosive mass and the chamber loading density for No. 1-2 were relatively small compared to those for No. 1-1 and 1-3 and the breaking of structural materials into smaller fragments had not progressed. It is not easily explained only in terms of loading density, but a scale effect should be taken into the consideration.

4. Conclusion

To establish safety standards for subsurface magazines, the effects of the structure and loading density of the chambers on the fragment distribution were evaluated using scale models of box-shaped and arch-shaped chambers constructed underground. The fragment distributions were measured and analyzed. There were no significant differences between the fragments from the box-shaped and arch-shaped chamber structures, although there was a tendency that heavier fragments were scattered a short distance from the arch-shaped chamber than from the box-shaped chamber. Comparing the fragments for different chamber loading densities and the same arch-shaped structures, the numbers of fragments for small loading density of 3 $kg{\cdot}m^{-3}$ was clearly smaller than the number for a loading density of 5 $kg{\cdot}m^{-3}$. In general, the effect of a blast wave may be treated deterministically, while the effect of projections including secondary debris may be treated probabilistically. Therefore, further experimental evaluations of the properties of debris from subsurface magazines under various conditions are required to minimize the uncertainties in the probabilistic results and obtain a good understanding of debris hazards, and the effect of cover depth and loading density on the debris distribution will be reported in our next paper.

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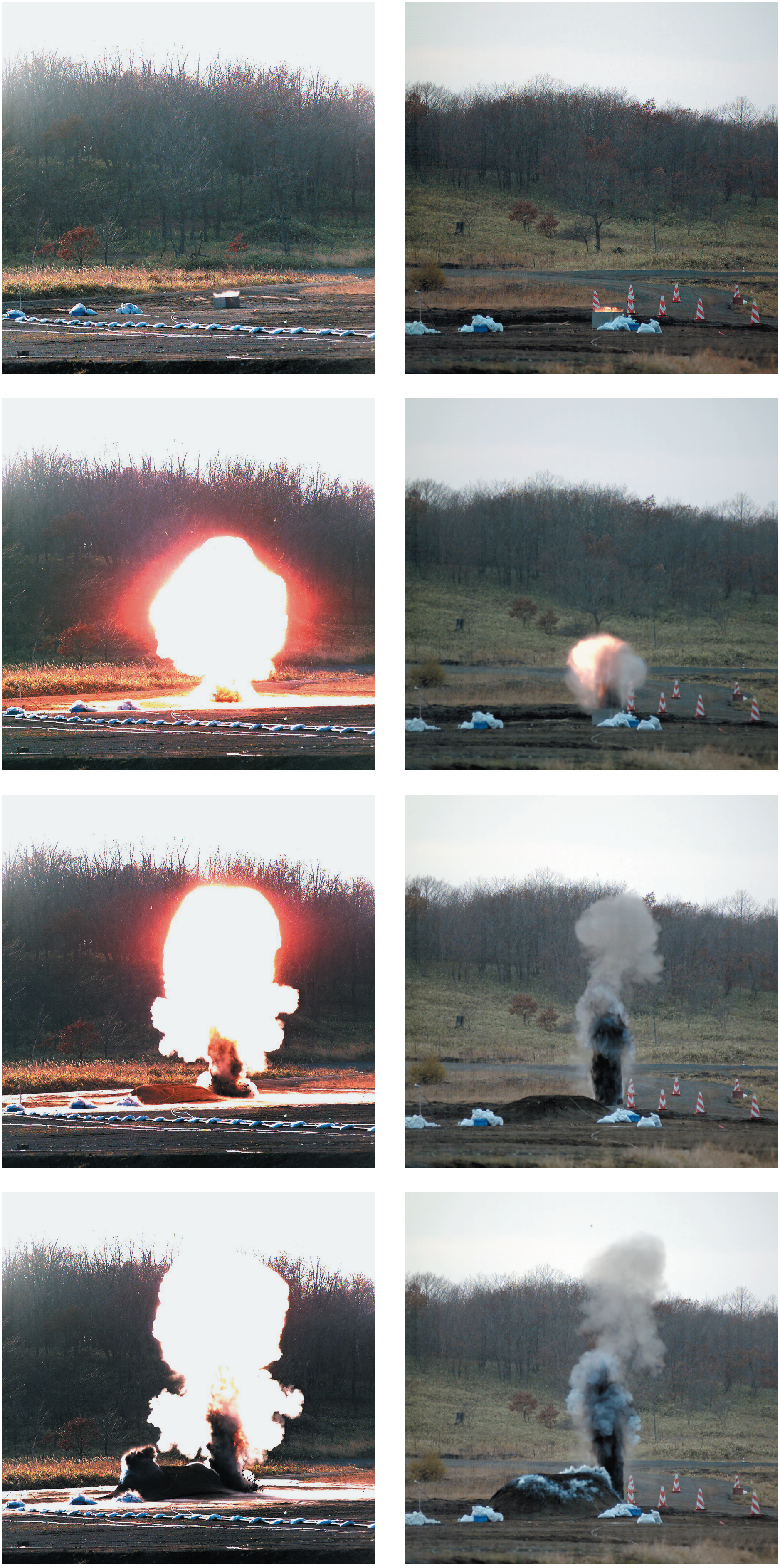

Figure 4 High−speed video images of explosions (left : 2, 23, 40, 60 ms for No.1-1, right : 1, 9, 40, 60 ms for No.1-3).

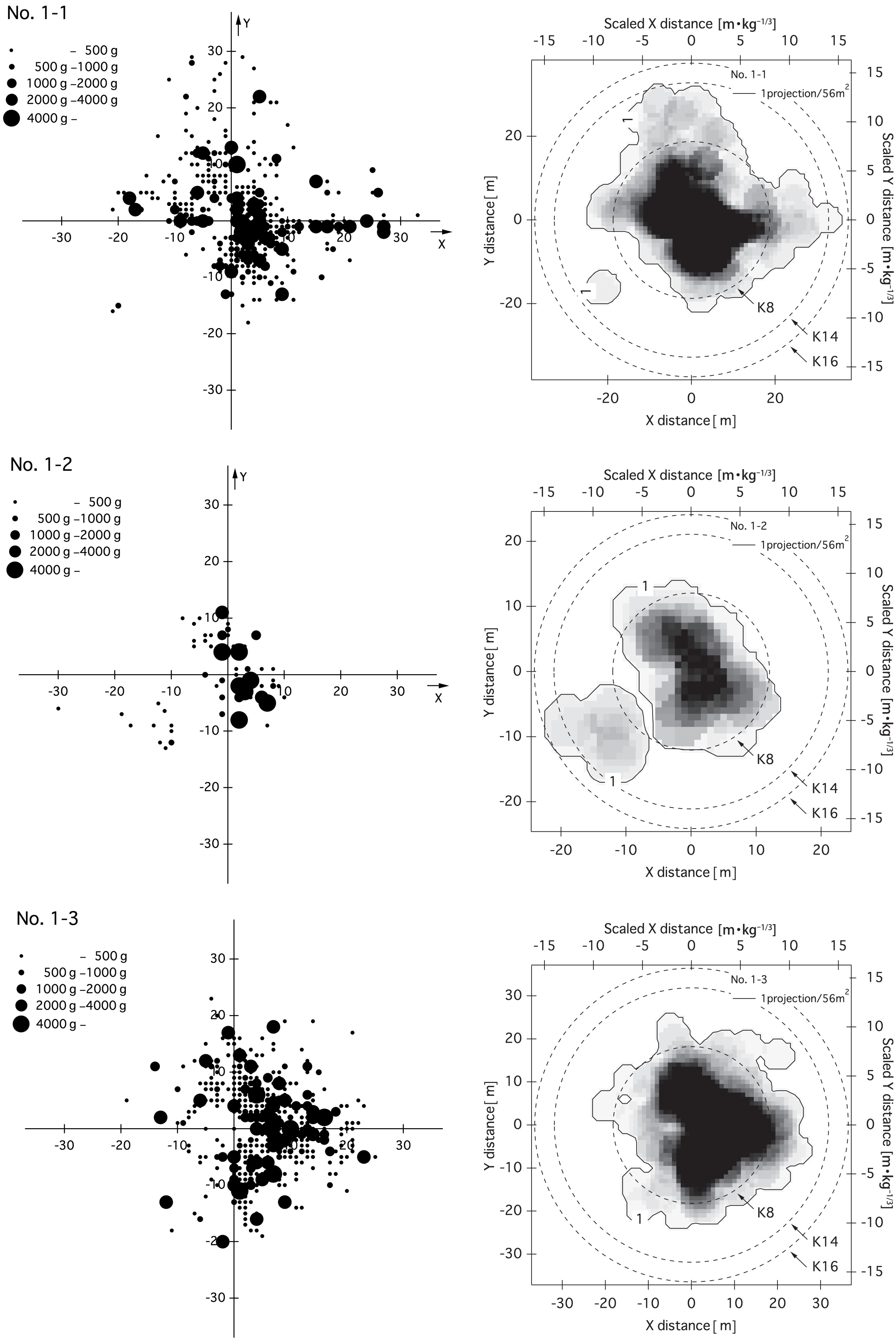

Figure 5 Fragment distributions (left) and hazardous areas (right) for No.1-1, 1-2, and 1-3.

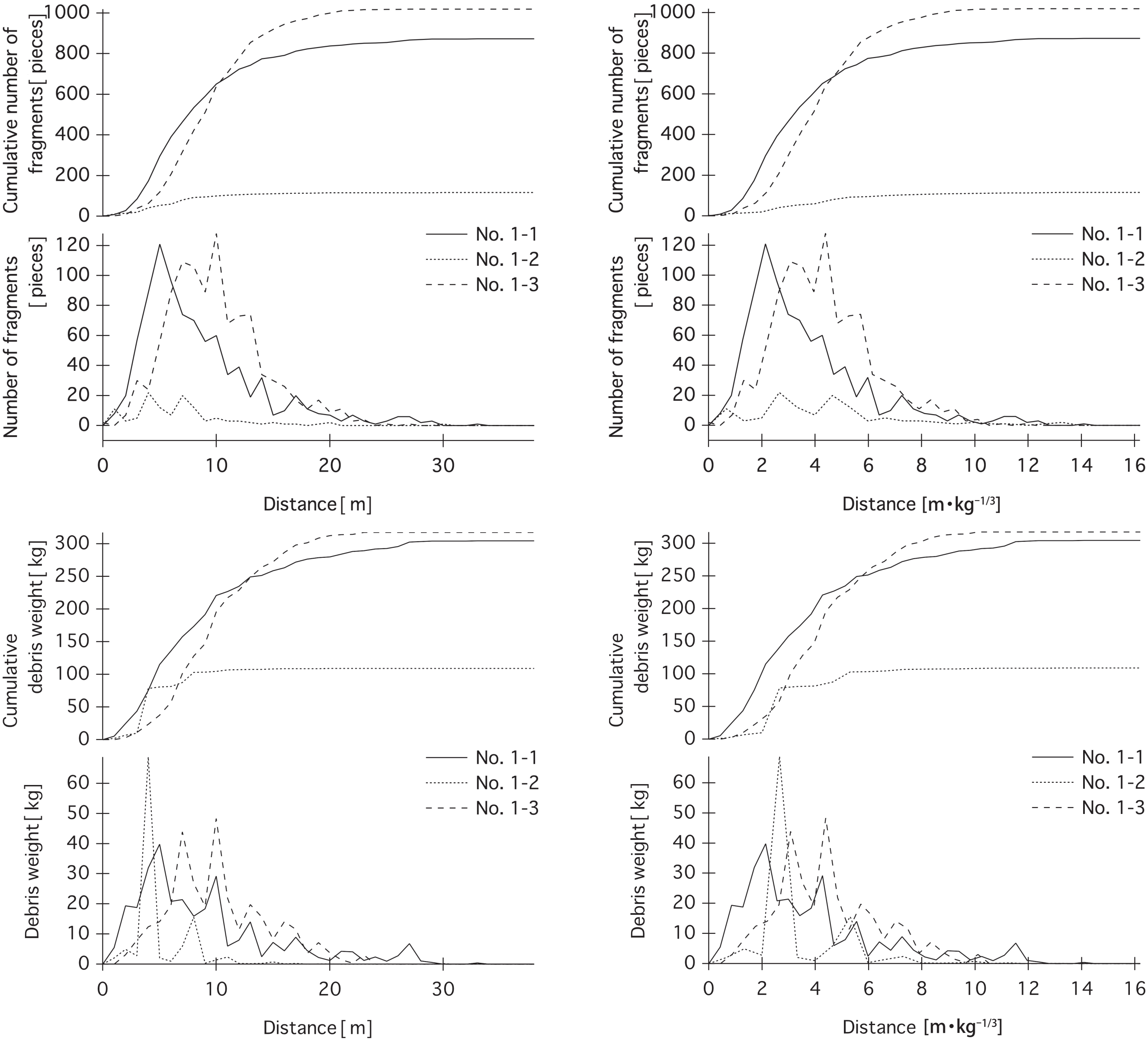

Figure 6 Distribution of number of fragments (top) and weight (bottom)plotted against absolute (left) and scaled (right) distances from the explosion source.

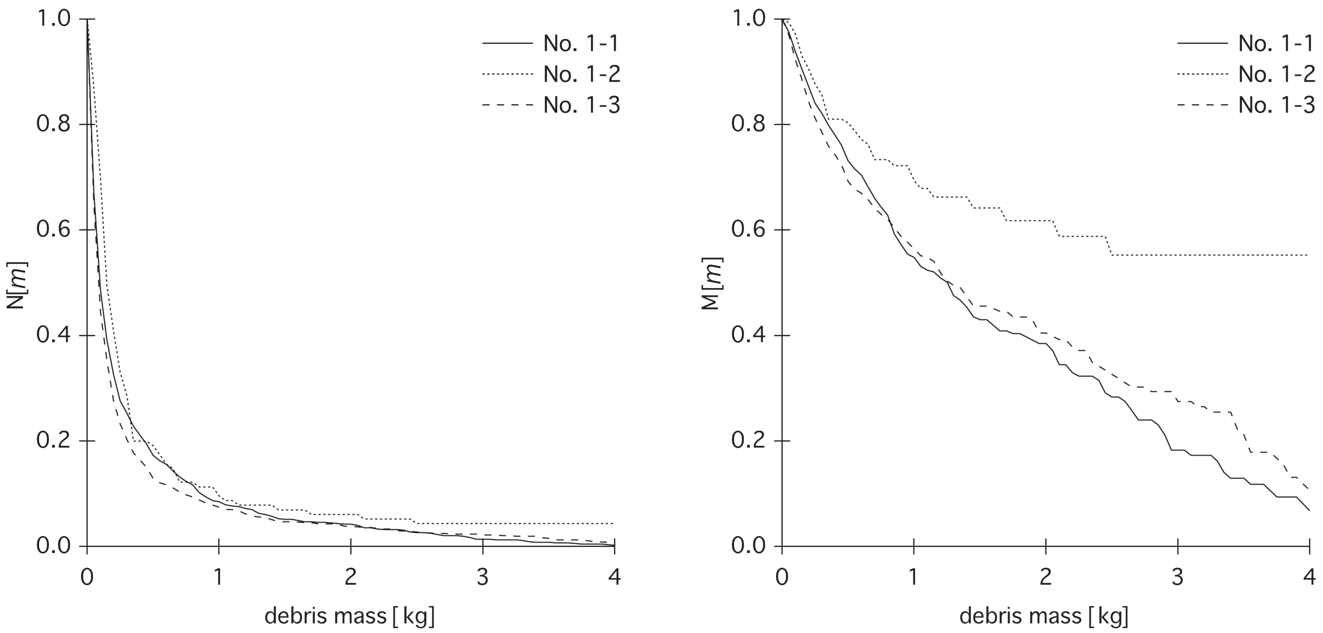

Figure 7 Debris mass distributions in the form of normalized cumulative number of fragments (left) and normalized cumulative debris mass (right).

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地下式火薬庫からの飛散物影響に関する実験的研究

佐分利禎*†，久保田士郎*，加藤勝美，緒方雄二***

火薬庫などの火薬類取扱い施設での爆発事故は爆風圧とともに危険飛散物を発生する。地下式火薬庫はこのような被害を軽減し，保安距離を縮小することが期待されている。地下式火薬庫は地中に建設され，貯蔵室，通用路，エレベータシャフトから構成されている。地下式火薬庫の爆発に伴う危険飛散物の影響評価は安全性評価の観点から重要であり，本研究では地下式火薬庫の爆発により発生する飛散物を実験的に評価した。ボックス型とアーチ型構造を持つ縮小モデル火薬庫を準備し，所定の薬量容積比でC４爆薬を内部爆発させて実験を行った。地下式火薬庫の適切な設置や設計基準を確立し，また飛散物に関する保安距離評価に貢献するため，飛散物数量–距離，飛散物量–距離などの関係を評価した。

*独立行政法人産業技術総合研究所安全科学研究部門　〒305−8569　茨城県つくば市小野川16−1
Phone：029−861−8760
†Corresponding address：t.saburi@aist.go.jp

**福岡大学工学部化学システム工学科　〒814−0180　福岡県福岡市城南南区七隈8−19−1