Research paper

Experimental studies on ground vibration from explosions in subsurface magazines

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Abstract

The ground shock vibration caused by an accidental explosion in a subsurface magazine was experimentally evaluated. The subsurface magazine was designed and proposed to meet the requirement of reducing the quantity-distance criterion. A subsurface magazine is constructed in the ground to mitigate the explosive hazard, and the exit from the storage chamber is a vertical elevator. Although the construction of the magazine in the ground is expected to reduce the effects of the airblast induced by an accidental explosion, the effect of the ground shock resulting from the explosion energy directly imparted to the ground becomes important. Two types of scale-model magazine equipped with a vertical transport shaft were designed and constructed underground, and scaled internal explosion tests using Composition C4 explosive were conducted while varying the chamber loading density. The effects of explosions from the subsurface magazines on the ground vibrations were measured and analyzed. The results of the study are expected to provide a basis for establishing design criteria for subsurface magazines.

Keywords : explosions, ground vibration, subsurface magazine.

1. Introduction

Three types of permanent explosive storage magazine are now regulated in the Explosives Control Act in Japan : above-ground magazines, earth-covered (igloo-type) magazines, and underground magazines. However, the number of cases in which it has been difficulty to satisfy the explosives safety quantity-distance (ESQD) owing to the construction of magazines in limited spaces has 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 an accidental explosion in the magazine on the air blast pressure and ground vibration should be evaluated. Although there have been reports on the air blast effects of the moisture content in the soil[4)] and the storage structure[5)] on the air blast and on the relation between the blast wave and explosive loading density[6)], there have been few reports on the effects of explosions on ground vibration. The effect of ground vibration resulting from an accidental explosion underground becomes more important than that resulting from an explosion occurring at or near the ground surface. Therefore, 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[7)] to acquire data on the ground vibration caused by accidental explosions. Two types of subsurface magazine with box-shaped and arch-shaped storage chambers were constructed and tested. The effects of changing the chamber loading density were evaluated for the arch-

Table 1 Test cases.

	No. 1-1	No. 1-2	No. 1-3
Explosive charge quantity Q [kg]	12.85	3.43	11.8
Storage chamber volume [m^3]	2.57	1.14	2.36
Chamber loading density (explosive mass per unit chamber volume)[$kg \cdot m^{-3}$]	5	3	5
Standoff from floor to center of explosive [cm]	8.6	10.7	19.6
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
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

shaped chamber. Ground vibrations were measured using acceleration sensors, and peak particle velocities (PPVs) were evaluated as a function of the scaled distance. The results of the study are expected to provide a basis for establishing design criteria for subsurface magazines.

2. Experiment

Accidental explosions in subsurface magazines exhibit a complex behavior in which various factors affect the resulting ground vibrations. The dominant factor is the chamber loading density, which is the amount of explosive per chamber volume. The properties of the media surrounding the chamber and the cover depth are other factors. To investigate the effects of differences in the magazine storage structure and chamber loading density, three tests denoted Nos. 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 tests 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 tests No. 1-1 and 1-2.

2.1 Explosive

Composition C-4 explosive was used in the experiments. The C-4 charges were weighed out so that the explosive chamber loading density was 5 $kg \cdot m^{-3}$ for tests No. 1-1 and 1-2 to compare the box-shaped and arch-shaped structures at the same loading density, and 3 $kg \cdot m^{-3}$ for test No. 1-2 to compare the effect of the loading density for the same arch-shaped structure in tests No. 1-1 and 1-2 as shown in Table 1. Explosive charges were housed in a wooden box in tests No. 1-1 and 1-3 and were arranged in a sphere in test No. 1-2. All charges were located in the center of the chamber at a certain standoff from the floor. The C-4 charges were initiated with a double-fold detonating fuse and two exploding-bridgewire detonators (EBWs). The total length of the detonating fuse was 16 m in test No. 1-1 and 1-3 and 14 m in test 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 chamber cover depth and scaled chamber cover depth are shown in Table 1, along with the chamber structure dimensions. 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 #1, #2, and #3 were 1700×1300, 674×900, and 500×1300 mm, respectively. The excavation depth used to install the chamber underground is illustrated in Figure 1. The soil classification comprising the surrounding ground is also illustrated in Figure 1 according to JGS 0051-2000[8]. The testing field was mainly composed of volcanic sediments from a nearby volcano. The surface soil layer was a fine SAND (SF) and the underlying layer was composed of alternating beds of SILT (M) and Sandy GRAVEL (GS), and the layer beneath the alternating bed was Organic SOIL (O). Photographs of the underground installation of the model magazines are shown in Figure 2.

2.3 Measurements

The ground vibration was measured using acceleration sensors. The measurement points were placed in certain intervals based on the scaled distance and they are shown in Table 2 and Figure 3. The reference point for distances determined for ground vibration measurement was on the ground surface directly above the ignition point in the underground chamber. A PCB M350B03 (0.5 $mV \cdot g^{-1}$, 100000 $m \cdot s^{-2}$) single-axis accelerator sensor was used in combination with an H-TECH 30622 linedriver and a 30510 receiver at point P1,directly above the explosion source,

Table 2 Measurement points for ground vibration.

	Distance [m] and scaled distance K (in parentheses)[$m \cdot kg^{-1/3}$] from ignition point		
Measurement point	No. 1-1	No. 1-2	No. 1-3
P1	0	0	0
P2	1.17 (0.5)	1.13 (0.75)	1.14 (0.5)
P3	4.68 (2)	4.5 (3)	4.55 (2)
P4	9.37 (4)	9.0 (6)	9.11 (4)
P5	18.74 (8)	18.0 (12)	18.21 (8)
P6	36.0 (15.5)	36.0 (24)	--

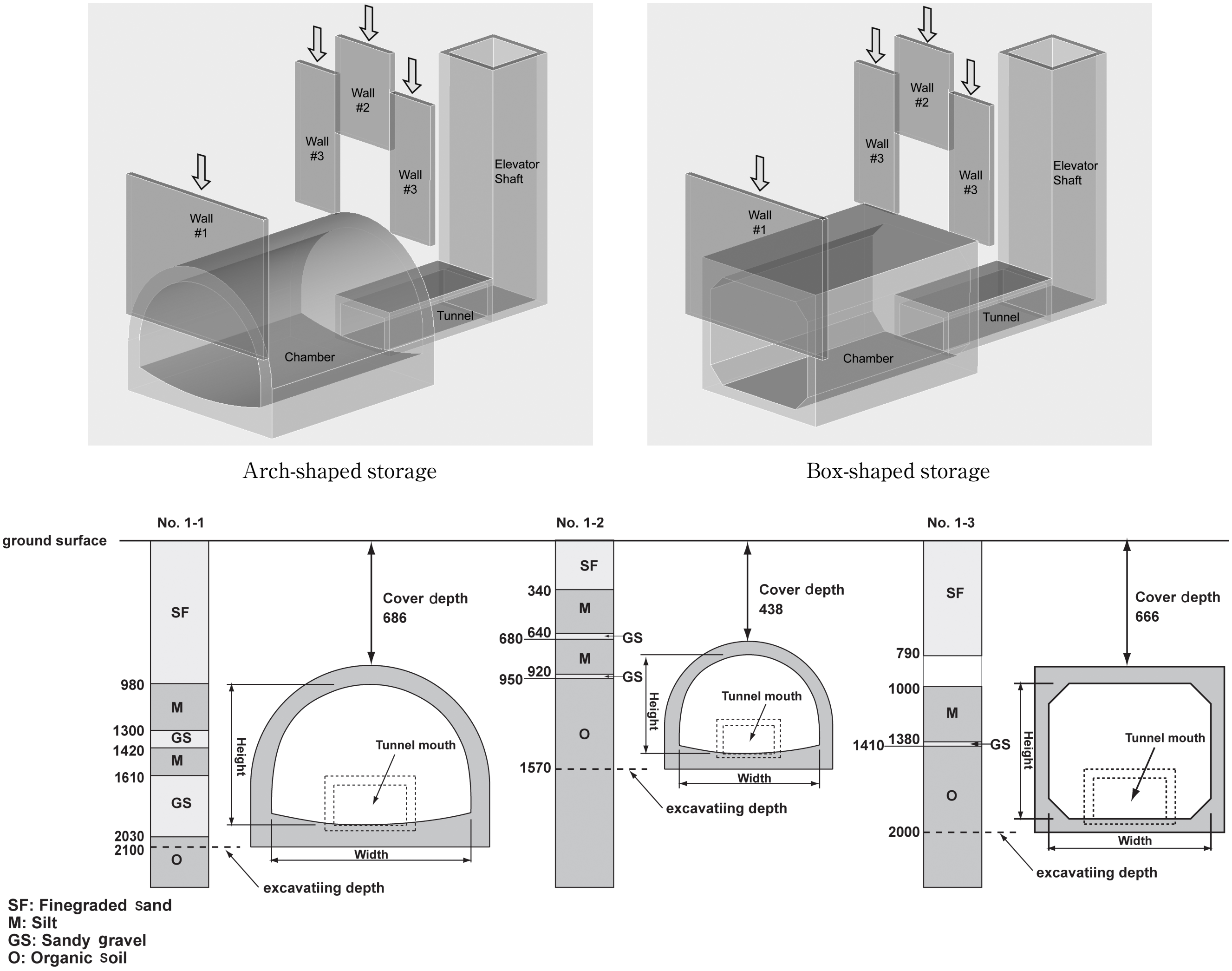


Figure 1 Schematic drawings of the arch-shaped and box-shaped storage chambers with culvert structures (top). Installation conditions of the chamber and soil classification of surrounding ground (bottom, in cm).

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

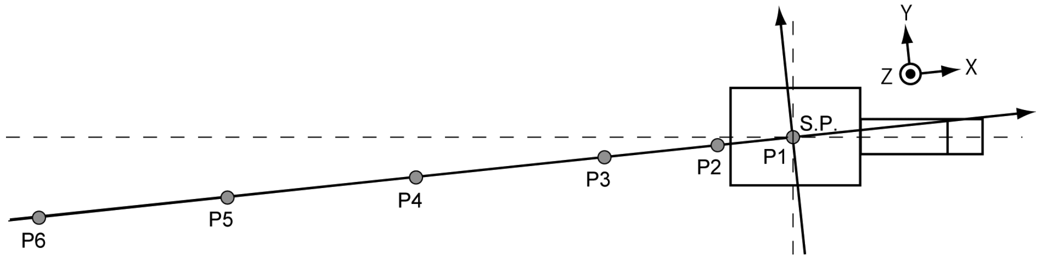


Figure 3 Layout of accelerator sensors and reference axes for vibration measurement.

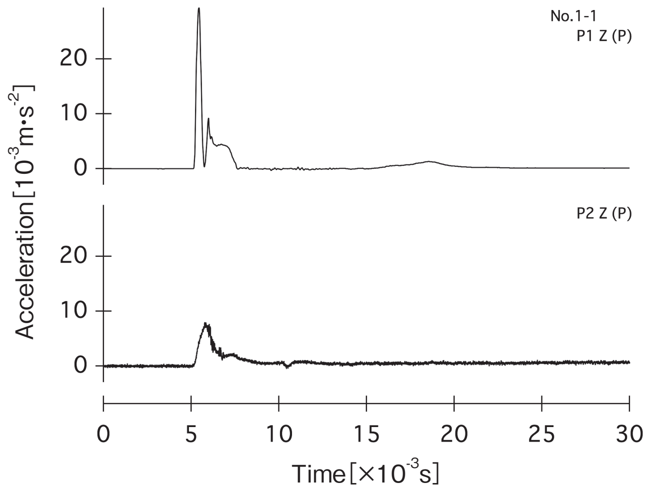
and a TEAC 612ZS (1.6pC·g^{-1}, 10000 $m{\cdot}s^{-2}$, 20kHz bandwidth) and a 707Z (100 mV·g^{-1}, 150 $m{\cdot}s^{-2}$, 30kHz bandwidth) tri-axial accelerator sensor were used in combination with a TEAC SA-611 amplifier at points P2-6. All signals from the SA-611 amplifiers were transmitted through 100 m long 3D2V coaxial cables with BNC connectors and were recorded with a TEAC LX-20 recorder at a 50kHz sampling rate. The overall frequency response characteristic of measuring system was estimated over 10kHz (-3dB). The signal recordings were started by a trigger signal synchronized with the ignition signal.

3. Results and discussion

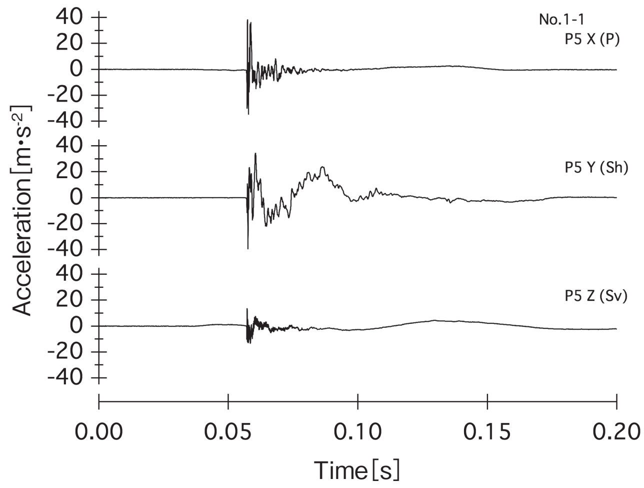
Figure 4 shows the evaluated acceleration signals in the x, y, and z direction at points P1-6 for test No. 1-1. The digital profiles of voltage measured with the sensors had the signal trend removed and were convolved and filtered out with a 0.5Hz high-pass filter and a 2000Hz low-pass filter using a Hanning window. Then, the acceleration signals were obtained by multiplying the voltage by the sensitivity of the sensor and amplifier unit. Seismic waves traveling under the ground as a result of explosion are body waves, and there are two types of body waves ; one is a primary wave (P-wave) and the other is a secondary wave (S-wave). The P-wave is a longitudinal wave or a compression wave, which is parallel to the traveling direction of the wave, and is the first arrival wave called initial tremors. The wave has characteristics of rapid vibration damping in the weak ground. S-wave is a transverse wave or a shear wave, which is perpendicular to the traveling direction of the wave, and travels slower than P-wave and causes the large vibration called principal motion. There are another waves traveling along the ground surface called surface waves comprising Rayleigh waves and Love waves. The waves have characteristics of long period, large amplitude, and low damping, and they are slower and more destructive than body waves especially far from explosion source. From the measured signals as shown in Figure 4, it was possible to identify the time of arrival of P-wave, but it was difficult to identify subsequent times of arrival of such S-wave or surface waves due to the interference of air induced ground shock. The velocities of P-wave were estimated for No. 1-1 to 1-3 : 1380 $m{\cdot}s^{-1}$ for No. 1-1, 980 $m{\cdot}s^{-1}$ for No. 1-2, and 1120 $m{\cdot}s^{-1}$ for No. 1-3. These velocities are classified into between dry soil and saturated soil[10], and it is reasonably consistent with the soil classification of the test field.

Sonograms of the short-time Fourier transform and power spectrum density (PSD) using periodogram for the signal obtained by computing Fourier spectra using a sliding window for test No. 1-1 at point P3 are shown in Figure 5. PSD is a frequency-domain plot of power per Hz against vibration frequency and the periodogram computes PSD for entire vibration signal. Ground shock contained a high-frequency component at the wave arrival time predominantly in a longitudinal wave in the x-direction (parallel to the direction of propagation) and a vertical transverse wave in the z-direction but the high-frequency component had a short duration and rapidly disappeared. It was considered that high-frequency P-wave was rapidly damped in the weak ground. On the other hand, a low-frequency component of up to 20Hz remained for a long time, resulting in ground vibration with a strong amplitude after the arrival of the wave. This was due to the low-frequency and large amplitude of surface waves or S-wave. Examples of ground vibration, which can be obtained by integrating the acceleration profiles, are shown in Figure 5(d) for Point P1 in test No. 1-1 and in Figure 6 for Points P1 and P2 in test No. 1-1. Figure 6 shows that the soil above the chamber was blown upward at 30-40 $m{\cdot}s^{-1}$ owing to the rupture of the chamber roof. As for Point P2 in Figure 6, the cable wiring was disconnected at 100 ms due to the throw of the sensor beyond the wiring length limit and the cable disconnection.

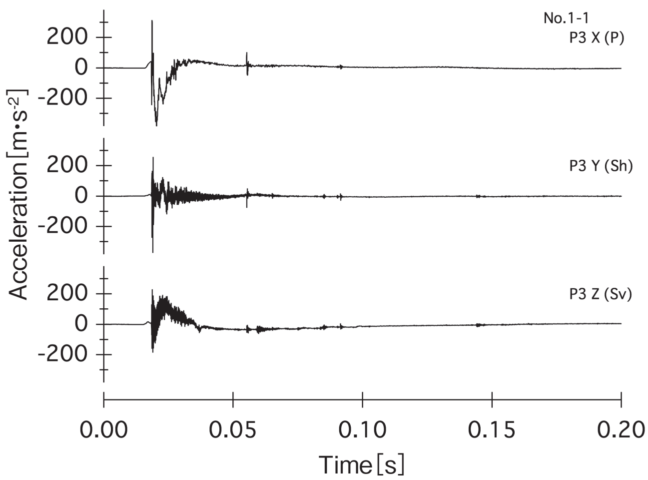
A ground vibration hazard criterion is usually evaluated using the PPV at which a certain level of damage is expected. The ground vibration is summarized in terms of PPVs in Figure 7, which were obtained by integrating and analyzing the measured acceleration profiles for each sensor channel in each test. In Figure 7(left), the X components (source point direction on the ground surface) and Z components (vertical direction) of the PPVs were prominent, particularly near the explosion source, and this tendency gradually become less apparent with increasing distance from the explosion source. In Figure 7(right), horizontal and vertical PPVs ($PPV_H = \sqrt{(PPV_x^2 + PPV_y^2)}$, $PPV_V = PPV_z$) as well as PPV lines for soil, saturated soil and rock evaluated using Westine's equation[9] and parameters for geological media[10] are plotted against scaled distance. It was found that most of the PPVs obtained experimentally lie almost between the PPV lines for soil and saturated soil, as expected for the experimental setup. The box-shaped structure appears to have less effect on reducing the maximum PPVs than the arch-shaped structure. The installation site for the



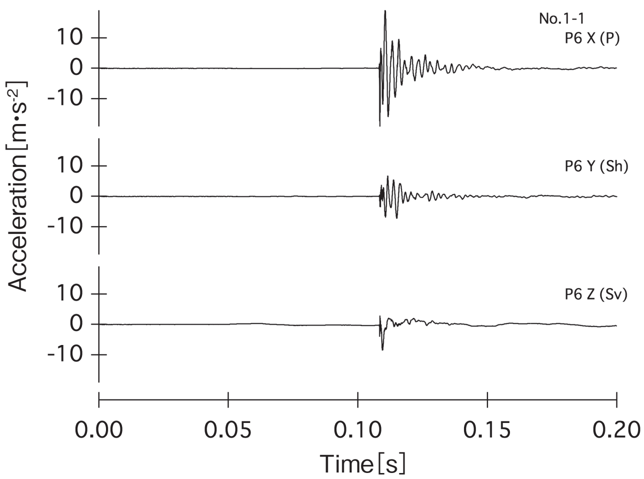
Point P1 : Distance 0 m-K0, Point 2 : 1.17 m-K0.5



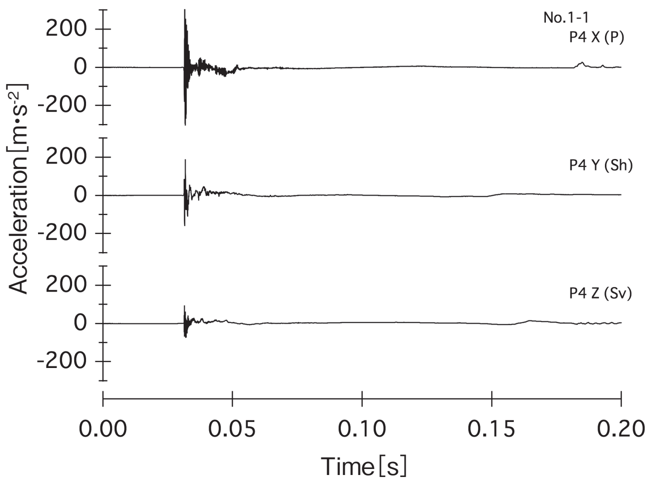
Point P5 : Distance 18.74 m-K8



Point P3 : Distance 4.68 m-K2



Point P6 : Distance 36 m-K15.5



Point P4 : Distance 9.37 m-K4

Figure 4 Measured acceleration signals in x, y, and z directions for test No. 1-1.

structure in test No. 1-3 was confirmed to contain a seepage groundwater, and it is suspected that there was an effect of the soil moisture in the ground on the PPVs obtained in test No. 1-3. Thus, it is considered that there is a clear difference in the ground vibration due to the difference in the chamber structure in the experiments. Regarding the effect of the chamber loading density in test No. 1-1 and 1-2, the lower chamber loading density of 3 $kg{\cdot}m^{-3}$ in test No. 1-2 resulted in larger maximum PPVs than those of for a loading density of 5 $kg{\cdot}m^{-3}$ in No. 1-1. The reason for this is unclear, and it is at least required the same explosive quantity to clarify this matter. The Department of Defense Explosives Safety Board (DDESB) defines the inhabited building distance (IBD) for a ground shock in the case of underground storage[3)], D_{ig} (m), as $D_{ig} = 0.91 \cdot f_g \cdot Q^{4/9}$ in soil, where Q is the quantity of

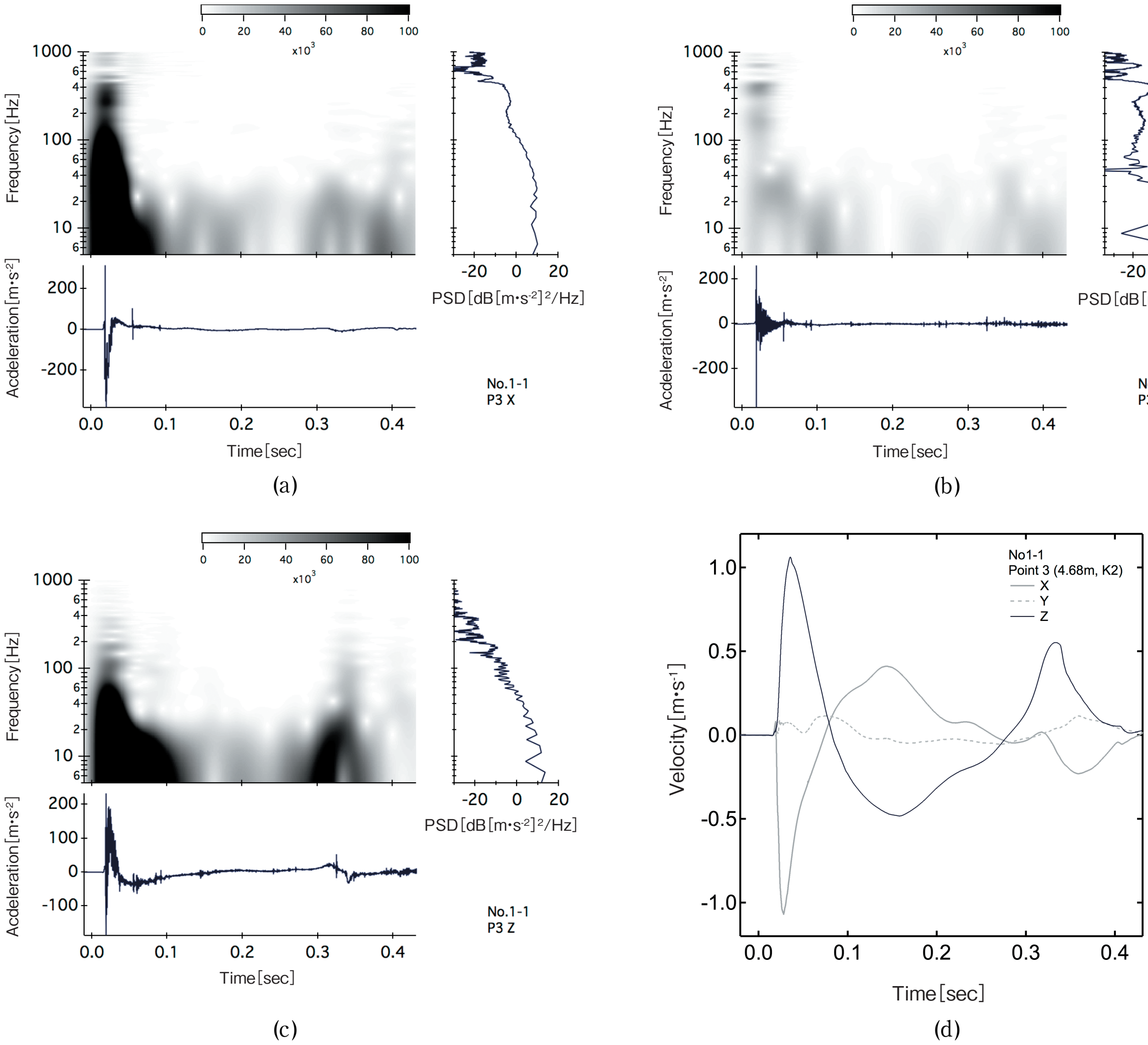


Figure 5 (a)-(c) Measured acceleration signals and analyzed sonogram and power spectrum density (PSD) for x, y, and z directions (a : X, b : Y, c : Z). (d). Integrated vibration velocity (V). (test No. 1-1, point P3, distance 4.68 m, K2).

explosive (kg) and f_g is a dimensionless decoupling factor that depends on the chamber loading density w (kg·m^{-3}); $f_g = 0.11604 \cdot w^{0.3}$. In this study, f_g is determined to be 0.188 for test No. 1-1 and 1-3 and 0.161 for test No. 1-2, and D_{ig} is evaluated to be 0.53 m for test No. 1-1, 0.25 m for test No. 1-2, and 0.51 m for test No. 1-3. It is believed that these values are underestimates in this scale-model study. DDESB also defines the maximum acceptable PPV for inhabited buildings in underground storage as 6.1 cm·s^{-1} in soil, 11.4 cm·s^{-1} in weak rock, and 22.9 cm·s^{-1} in strong rock[3]. From Figure 7, the scaled distance that satisfies the acceptable PPV for soil is about 10 m·kg^{-3}, less than the value of 16 m·kg^{-3} corresponding to K16 in the Japanese ESQD criteria.

4. Conclusion

To establish safety standards for subsurface magazines, the effects of the structure and loading density of the chamber on the ground vibration were evaluated using scale models of box-shaped and arch-shaped chambers constructed underground in the same geological condition. Ground vibrations were analyzed in terms of peak particle velocity (PPV), and the results were in reasonable agreement with the theoretical PPV line for soil. However, no significant difference in the ground vibration was observed between the box-shaped and arch-shaped chamber structures in the experiments. To discuss the effect of the scaled distance on ground vibration, careful

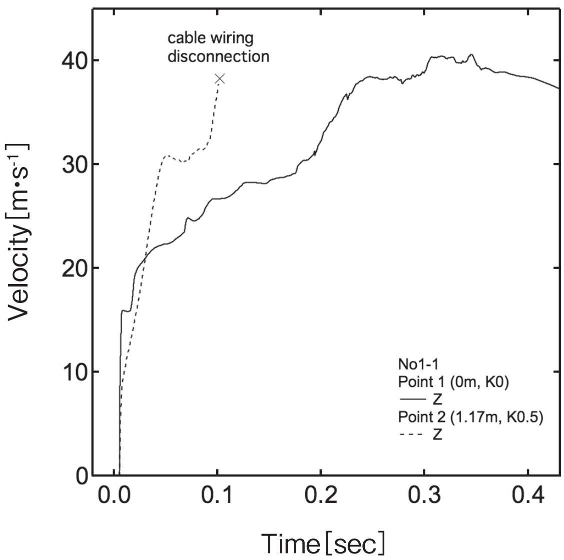


Figure 6 Integrated vibration velocity profile (test No. 1-1, points P1 and P2).

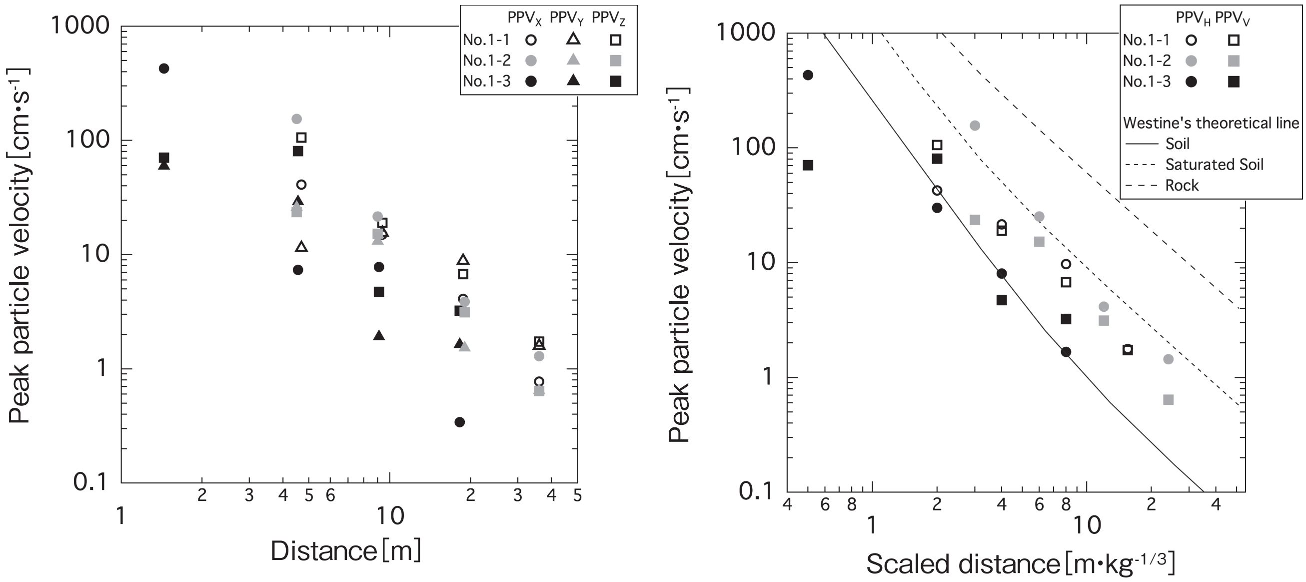


Figure 7 Peak particle velocity (PPV) for x, y, and z directions plotted against distance (left) and for horizontal and vertical directions plotted against scaled distance (right).

consideration is required because of scaling law of geological layer, propagation of seismic wave, and so on. More experimental evaluations will be performed over a wide range of scales and chamber loading densities.

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地下式火薬庫からの地盤振動影響に関する実験的研究

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地下式火薬庫での爆発事故で発生する地盤振動影響を実験的に評価した。地下式火薬庫は保安距離の緩和を可能にするために設計・提案されており，爆発被害を低減するために地下に建設し，貯蔵室からの搬入出は垂直エレベータで行うように計画されている。地下への火薬庫設置は爆発事故によって発生する衝撃波などの爆風影響を低減することが期待されるものの，周辺地盤に直接付与される爆発エネルギーによって発生する地盤振動の影響が重要になってくる。本研究では垂直シャフトを有する二種類の縮小モデル火薬庫を設計して地下に建設して，Ｃ４爆薬を用いて薬量容積比を変えて内部爆発実験を実施した。爆発によって発生する地盤振動を加速度センサーで観測し，地下式火薬庫の爆発による地盤振動影響を評価・分析した。

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