研究論文

Evaluation of magnitude of an explosion from dimensions of crater formed in ground comprising gravel under a concrete slab

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Crater size, which is directly obtainable from the effects of an explosion, is regarded as an important qualitative measure of its magnitude. The relationship between quantity of explosive and crater size has been examined in detail for various kinds of rocks and soils. However, no empirical equation for evaluating the magnitude of an explosion (relation between crater size of ground and charge mass) is available when an accidental explosion occurs above a concrete slab, and a crater is formed under the concrete slab. Most studies center on high explosives, and there is little data for smokeless powders. In the present paper, the relationship between crater size and charge mass for a high explosive and two types of smokeless powders are reported under conditions where a concrete slab is present between the explosive and the ground. We also estimated TNT equivalents for smokeless powders from crater volume. The observed results were compared with the calculated values and a reasonable agreement was found.

1. Introduction

If an accidental detonation of explosives occurs inside a structure such as explosives magazine or chemical plant, the magnitude of the explosion needs be correctly evaluated to identify the cause of the accident. At present, this is done by combining information on the size of the resultant crater, breakage of windows, damage to facilities, and surrounding buildings, people and animals. The size of the resultant crater is an important qualitative index of magnitude of the explosion close to the explosive charge. The relationship between the quantity of explosive and crater size have been examined in detail for various kinds of rocks and soils, and it has been reported that resultant crater volume is proportional to TNT equivalent mass, and the resultant crater diameter and depth are proportional to the cube root of the charge mass[1-3]. When the surface of solid slabs (including concrete slabs) were exposed to detonation of explosives, it has been reported that the crater size closely depends on the length-to-diameter ratio of the charge, L/D (L = charge length and D = charge diameter); crater depth is proportional to charge diameter; and the resultant crater volume is proportional to the square root of the charge mass[4,5]. If an accidental explosion at a real storage site is assumed, the explosives are stored in a container placed above the concrete floor which in turn covers a layer of gravel. Under these conditions, the concrete slab is perforated and a crater forms underneath. No studies have been carried out on the relationship between crater size in the ground and charge mass under these conditions. In addition, the studies that have been carried out are based on experiments with high explosives. There is little data for smokeless

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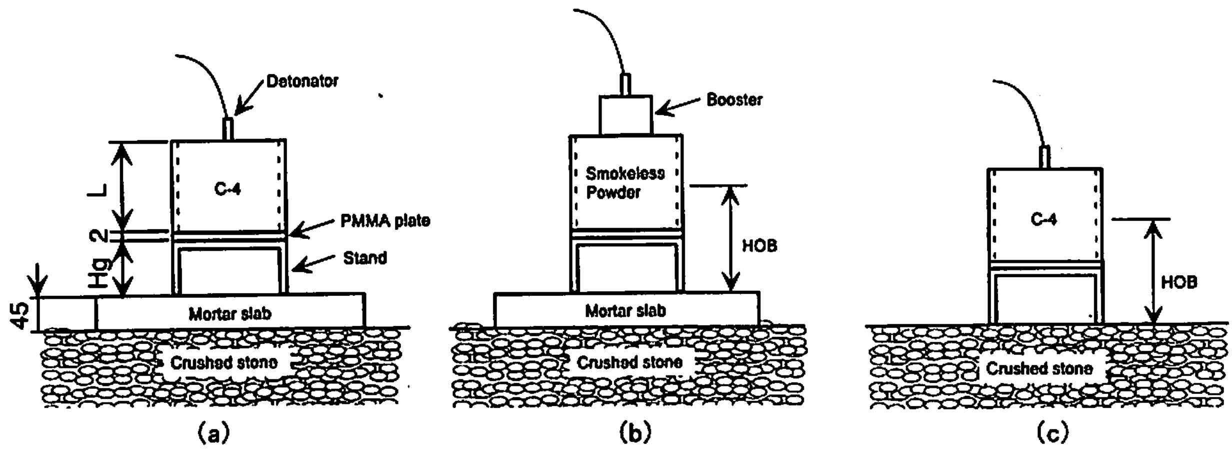

Fig. 1 Experimental setup

powders.

The purpose of this paper was to gain an understanding of the relationship between crater size and charge mass for high explosives and smokeless powders under conditions where a concrete slab is present between the explosive and the ground and to propose equations expressing these relations. Also, the TNT equivalent of two smokeless powders are estimated by crater size and compared with the calculated values.

2. Experimental setup

Figure 1 shows the explosive, and the installation of concrete slabs with $H_g = 70$ mm; (a) C-4, (b) smokeless powders, and (c) C-4 with no concrete slab. H_g is defined as the distance between the lower surface of a PMMA plate (2 mm in thickness) and the front surface of the concrete slab or the ground. Two different gaps, $H_g = 0$ mm and $H_g = 70$ mm, were used to examine the effects of height of burst (HOB). HOB is defined by the distance from the center of the explosive to the surface of the concrete slab, or to the surface of the ground in the case of no concrete slab being present. Therefore, the relation between HOB (m) and H_g (m) is expressed by HOB = $(L/2) + 0.002 + H_g$. Table 1 shows the explosives used in the present experiment: mass, diameter, and length. Although TNT is often used in large-scale experiments, C-4 (RDX 90. 2, plasticizer 9. 5, other ingredients 0. 3 wt.%) (Nippon Koki Co, Ltd.) was chosen as the standard explosive in the present experiment. The reason for this selection is that the present experiments were conducted on a small scale and reference data are available for C-4[4, 5]. A single base propellant, 35GIP (NOF Corp.) and a double base propellant, SS (NOF Corp.) were used as typical smokeless powders since the two smokeless powders were found in a preliminary experiment to be detonable. C-4 and the smokeless powders were loaded into a cylindrical container made of polyvinylchlorate or MC nylon. The average loading density was 1400 $kg \cdot m^{-3}$ for C-4, 521 $kg \cdot m^{-3}$ for 35GIP and 616 $kg \cdot m^{-3}$ for SS. The charge mass of C-4 varied from 0. 025 kg to 4. 3 kg and that of the smokeless powders was 5. 0 kg. Since the L/D of the explosive had a strong influence on the crater size, $L/D = 0.75$ was used in the present experiment[4]. C-4 of 0. 25 kg in mass loaded in a plastic container (50 mm in diameter × 67 mm in height) was used as a booster explosive for the two types of smokeless powders. C-4 was detonated with a No. 8 electrical detonator (Hokkaido NOF Corp.).

The sizes of the concrete slabs were determined as follows. The concrete slab thickness, the diameter of the reinforcing bar, and gap length were assumed to be 120 mm, 6 mm, and 210 mm, respectively for a full-scale structure. Since the present experiment was scaled down to about one-third, the thickness of the concrete slab, diameter of reinforcing bar, and gap were given values of 45 mm, 1. 6 mm, and 70 mm, respectively. Table 1 shows the sizes of the concrete slabs. Each concrete slab was made of conventional Portland cement and river sand. The mixing proportion was cement : sand = 600 : 1436, and the water-cement ratio was w/c = 280/

Table 1 Experimental conditions and results of crater dimensions

Exp. No	Explosive	Charge mass (kg)	Charge diameter (m)	Charge length (m)	Gap length* (m)	Scaled HOB** ($m \cdot kg^{-1/3}$)	Mortar slab size (m)	Crater size $a \times b \times L_a$ (m)	Apparent crater volume (m^3)
1	C-4	4.331	0.175	0.132	0.	0.042	2.20×2.20×0.045	0.590×0.550×0.115	1.47E-02
2	C-4	0.987	0.107	0.080	0.	0.042	1.14×1.14×0.045	0.310×0.310×0.080	3.02E-03
3	C-4	0.250	0.067	0.050	0.	0.043	0.72×0.72×0.045	0.205×0.180×0.051	7.39E-04
4	C-4	0.071	0.044	0.033	0.	0.045	0.45×0.45×0.045	0.105×0.095×0.020	7.83E-05
5	C-4	0.025	0.031	0.023	0.	0.046	0.27×0.27×0.045	0.095×0.130×0.021***	1.02E-04***
6	C-4	4.357	0.175	0.132	0.070	0.084	2.20×2.20×0.045	0.420×0.440×0.100	7.26E-03
7	C-4	0.991	0.107	0.080	0.070	0.112	1.14×1.14×0.045	0.230×0.240×0.045	9.75E-04
8	C-4	0.250	0.067	0.050	0.070	0.154	0.72×0.72×0.045	0.165×0.165×0.005	5.35E-05
9	C-4	0.071	0.044	0.033	0.070	0.214	0.45×0.45×0.045	0.084×0.087×0.014***	4.02E-05***
10	C-4	0.986	0.107	0.080	0.	0.042	Without slab	0.330×0.340×0.085	3.75E-03
11	C-4	0.462	0.083	0.062	0.	0.043	Without slab	0.240×0.220×0.045	9.33E-04
12	C-4	0.250	0.067	0.050	0.	0.043	Without slab	0.240×0.230×0.035	7.59E-04
13	C-4	0.025	0.031	0.023	0.	0.046	Without slab	0.260×0.250×0.032	8.17E-04
14	35GIP****	5.000	0.249	0.197	0.	0.056	2.20×2.20×0.045	0.390×0.350×0.190	9.45E-03(1.02E-02)*****
15	35GIP****	5.000	0.249	0.197	0.070	0.097	2.20×2.20×0.045	0.410×0.430×0.140	9.64E-03(9.69E-03)*****
16	SS****	5.000	0.235	0.187	0.	0.053	2.20×2.20×0.045	0.370×0.360×0.180	8.68E-03(9.42E-03)*****
17	SS****	5.000	0.235	0.187	0.070	0.094	2.20×2.20×0.045	0.430×0.400×0.130	8.73E-03(8.78E-03)*****

*: Defined by distance between lower surface of PMMA plate and the top surface of the concrete slab or ground

**: Height of burst defined by distance between the center of the explosive and the surface of the concrete slab or ground

***: Crater size formed in the top surface of the concrete slab.

****: Cylindrically shaped C-4 (0.25 kg) is used as a booster explosive.

*****: The figures in parentheses are the resultant crater volume resulting from both the smokeless powder and booster charge.

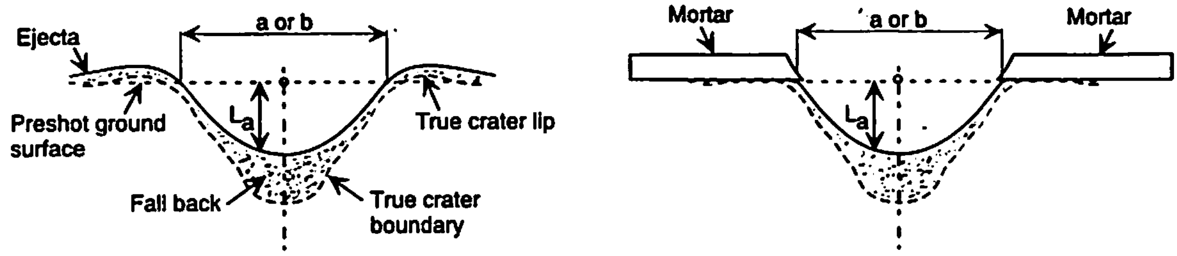

Fig. 2 Crater parameters: the left-hand figure indicates the case with no concrete slab and the right-hand figure with a concrete slab.

600. The concrete slabs were cured for twenty-two to thirty days, then kept indoors until the test. Sheets of wire mesh (wire diameter 1.6 mm) were imbedded in the slab at intervals of 30 mm to maintain its shape during curing. It was reported that the reinforcing bar had no appreciable effect on primary response (e.g. stress wave response) of the concrete slab[5]. Therefore, no consideration was given to the size and interval of the wire mesh. The density of the concrete slab was 3150 $kg \cdot m^{-3}$ and its compressive strength was 41.0 $N \cdot mm^{-2}$ after aging for 7 days, rising to 51.4 $N \cdot mm^{-2}$ after aging for 21 days. The floor underneath was made of gravel 5-13 mm in size (one-third normal size) with a density of about 1600 $kg \cdot m^{-3}$.

The major diameter, the minor diameter and the depth of the crater were measured to obtain the resultant crater volume as shown in Fig. 2. The craters were assumed to show the following characteristics: a) the horizontal cross section parallel to the ground surface was elliptical and b) the two orthogonal vertical cross sections were parabolic. The resultant crater volume V_a (m^3) was estimated using the following equation:

$$V_a = \frac{\pi}{8} a \cdot b \cdot L_a \qquad (1)$$

Here, a = major diameter of the horizontal cross section of the crater parallel to the ground surface (m); b = minor diameter of the horizontal cross section of the crater parallel to the ground surface (m); and L_a = depth of the crater (m).

3. Results and discussion

3.1 Perforation criteria of concrete slab

The relationship between charge mass and depth of perforation of concrete slabs resulting from surface blasting with C-4 is shown in Fig. 3. The boundary between the perforated and un-perforated region can be expressed as a straight line as follows.

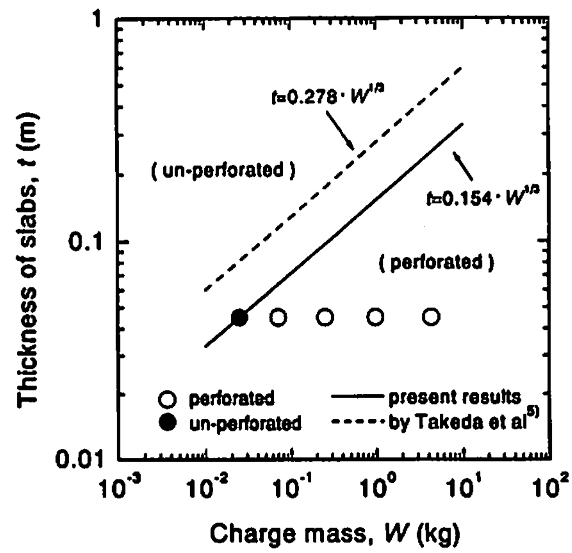

Fig. 3 Relationship between charge mass and perforated thickness of concrete slabs when surface blasting with C-4. Solid circle = un-perforated slab; open circle = perforated slab.

$$t = 0.154 \cdot W^{1/3} \qquad (2)$$

Where t = thickness of concrete slab (m), and W = charge mass (kg). Since Equation 2 is obtained from t = 0.045 (m), it may be not valid for another thickness. The results obtained by Takeda et al.[5] are also shown in Fig. 3 as a dotted line. The present results gave thinner values than Takeda's result. Since Takeda used five kinds of explosives including C-4 and masses ranging from 10 g to 600 kg, their results appear to give a thicker value than Equation 1. However, since Takeda's C-4 results were thinner than their own averaged data, it may be concluded that the present results show a good agreement with Takeda's C-4 results.

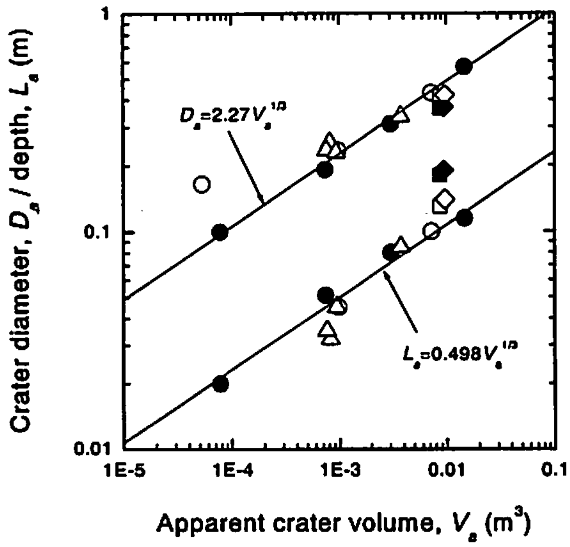

Fig. 4 Crater radii and depths as a function of the resultant crater volume.
Solid circle = C-4 with H_g = 0 mm; open circle = C-4 with H_g = 70 mm; open triangle = C-4 without concrete slab; solid square = SS with H_g = 0 mm; open square = SS with H_g = 70 mm; solid diamond = 35GIP with H_g = 0 mm; open diamond = 35GIP with H_g = 70 mm.

3. 2 The relationship between diameter and depth of the resultant craters

In the present experiments, D_a is considered to be the average crater radius, defined as $D_a = (a \cdot b)^{1/2}$. Figure 4 shows crater radius D_a and crater depth L_a as a function of the resultant crater volume. The results for C-4 with H_g = 0 mm were expressed using the following equations:

$$D_a = 2.27 \cdot V_a^{1/3} \quad (3)$$

$$L_a = 0.498 \cdot V_a^{1/3} \quad (4)$$

In Fig. 4, the solid lines show Equations 3-4. It was found that the results of C-4 with H_g = 70 mm with no slab present can be expressed using same equation. It has been reported that the radius and depth of craters from high-explosive sources in wet soil and those from high explosive and nuclear sources in dry soil, soft rock, and hard rock are best estimated using the following equations[1].

$$\left.\begin{aligned} D_a &= 2.4 \cdot V_a^{1/3} \\ L_a &= 0.5 \cdot V_a^{1/3} \end{aligned}\right\} \quad (5)$$

The values of the present experiment show a good agreement with Equation 5.

It was found that the crater depths for the smokeless powders were significantly deeper than in the C-4 data and that the crater diameters were shorter than in the C-4 data. In particular, the depths for smokeless powders with H_g = 0 mm were more than twice that of C-4 data for the same crater volume. The reason for this result is unknown, but it may be a feature characteristic of smokeless powders.

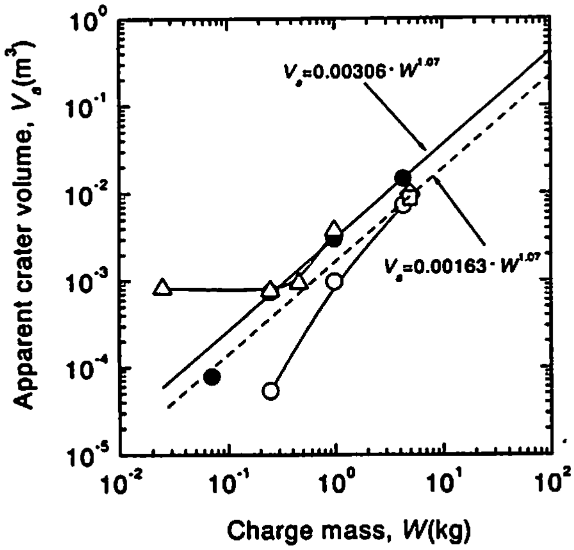

Fig. 5 The resultant crater volume as a function of charge mass. The symbols represent the same items as in Fig. 4.

3. 3 Resultant crater volumes as a function of charge mass

Table 1 shows the results for the major diameter, minor diameter, and depth of the resultant craters. Figure 5 shows the resultant crater volume as a function of charge mass. Since a good linear relation was obtained for the largest three masses of C-4 with H_g = 0 mm (scaled HOB of about 0.04 m$\cdot$kg$^{-1/3}$), the data were fitted using the following equation.

$$V_a = 0.00306 \cdot W^{1.07} \quad (6)$$

It was found that the resultant crater volume was approximately proportional to the charge mass[1,2]. The results for 0.071 kg were slightly smaller than the value given by Equation 6. This means that the scaling law is not applicable to small charge masses in the present results due to the size of the ground (gravel size is 5-13 mm).

In the data for H_g = 70 mm, V_a was smaller than the data for H_g = 0 mm, especially at small charge mass, since the smaller the charge mass, the higher the scaled HOB (scaled HOB increased from 0.084, to 0.112, to 0.154 $m \cdot kg^{-1/3}$ as shown in Table 1). The resultant crater volumes thus became smaller than the values predicted in Equation 6. The effect of HOB was clearly observed in the C-4 results.

Next, the results without a concrete slab are considered in Fig. 5. It is very interesting to note that, except for the smallest masses, the resultant crater volumes without a concrete slab closely paralleled those with a concrete slab. It is concluded that the slab was so thin that it showed no resistance to surface blasting under perforated slab conditions.

For the smokeless powders, the resultant crater volumes in the present experiment showed almost the same value regardless of H_g or type of explosive. It is clear that when H_g is higher, the pressure acting on concrete slab is lower, and smaller craters are likely to be formed on the concrete slab, as clearly observed in the C-4 results. The mechanism of crater formation by explosion on the surface of the concrete slab is considered to be via shock waves and/or reduction of material strength by the heat of the explosion[4]. Table 2 shows detonation properties such as detonation velocity, temperature, and pressure at the Chapman-Jouguet point (C-J point) and heat of explosion (HOE) calculated using the CHEETAH[6] and KHT[7] thermochemical codes for the loading density of each explosive. The pressures of smokeless powders are one fifth those of C-4 and TNT, but the temperatures are comparable. Takeda et al. mentioned the importance of the heating effects of hot detonation product gases. The relationship between crater depth and diameter for smokeless powder could not be explained solely by pressure effects in the present result; thermal effects may thus play an important role in the formation of craters.

Next, we propose an expression to describe the relationship between the resultant crater volume and the charge mass of a smokeless powder. Since the experiments were conducted with 5 kg of smokeless powders, the charge mass dependency needs to be known. In the present experiment, it is assumed that the dependency mass in the case of smokeless powders has the same value as that for C-4 with H_g = 0 mm. Therefore, the following expression is obtained for smokeless powders.

$$V_a = 0.00163 \cdot W^{1.07} \quad (7)$$

The range of parameters is W = 0.071-4.331 kg and H_g = 0-70 mm. This is shown in Fig. 5 by the dotted line.

3.4 TNT equivalent of smokeless powders

Here, the TNT equivalent of smokeless powders is estimated from the crater volume and the observed TNT equivalent was compared with the thermochemical calculation results. The comparison of calculated TNT equivalent to the observed data for two smokeless powders is shown in Table 3. The TNT equivalent is obtained from the ratio of the heats of explosions in the calculation. As a

Table 2 Detonation properties of explosives calculated using KHT and CHEETAH codes

		Composition C-4	Single base propellant 35GIP	Double base propellant SS	TNT
Loading density ($kg \cdot m^{-3}$)		1410	550	600	1600
Detonation velocity ($m \cdot s^{-1}$)	KHT	7198	3958	4176	6844
	CHEETAH	6991	3955	4155	6722
Detonation temperature (K)	KHT	3532	3227	3591	3428
	CHEETAH	3892	3455	3830	3712
Detonation pressure (GPa)	KHT	18.74	2.56	3.09	19.08
	CHEETAH	17.38	2.60	3.11	18.04
Heat of explosion ($MJ \cdot kg^{-1}$)	KHT	5.560	4.057	4.415	4.685
	CHEETAH	5.314	4.151	4.782	4.801

Table 3 Comparison of calculated TNT equivalent with the observed data for two smokeless powders

			C-4	Single base propellant 35GIP	Double base propellant SS	TNT
TNT equivalent	Calculated*	KHT	1.19	0.866	0.942	1.00
		CHEETAH	1.11	0.865	0.996	1.00
	Observed**		—	0.74	0.68	1.00

*; TNT equivalent is obtained from the ratio of the heats of explosions in the calculation

**; The observed C-4 equivalent of smokeless powders is obtained from equivalent apparent crater volume and it is converted to TNT equivalent by multiplying the factor of 1.19.

result, TNT equivalents calculated using the KHT code for C-4, 35GIP and SS were 1.19, 0.866 and 0.942, respectively. The results calculated using CHEETAH gave closely similar values. The observed C-4 equivalent mass of smokeless powders was estimated from Equation 6 and the resultant crater volume for $H_g = 0$ mm in Table 1. The observed TNT equivalent for smokeless powders was estimated from the value of the observed C-4 equivalent mass of smokeless powders multiplied by the calculated TNT equivalent of C-4 (1.19). The average of the observed results was found to be 30 % lower than the averaged calculated value (0.91 from KHT code). The one of reasons for this is that the length-to-diameter ratio was relatively small and a steady-state detonation may not occurred for the case of smokeless powders. Moreover, it is reported that the calculated and experimental pressure (and temperature) differ by 10 to 20 % for high explosives[8]. Since low explosives such as smokeless powders were used in the present experiment, the mechanism of crater formation is not fully understood. It may be concluded that the calculated values based on the heat of explosion and experimental values based on crater dimension agree to within 30 %.

4. Conclusions

To evaluate the magnitude of the explosion from the resultant crater volume in the case of ground made up of gravel under a concrete slab, we examined the relationship between charge mass and crater size, effects of scaled height of burst (HOB) and presence or absence of a concrete slab. In the case of C-4 and gap of 0 mm, it was found that the relations among the resultant crater volume, the diameter and depth agreed well with the reference data for various rocks and soils. Moreover, the effect of scaled HOB was clearly observed, and it was found that the presence or absence of a concrete slab had no appreciable effect in the present experiment. On the other hand, in the cases of two types of smokeless powders, the crater diameters were smaller and the crater depths were deeper than the data for C-4. Moreover, the crater volume was almost a constant value regardless of type of smokeless powder or gap. We propose an empirical formula by which the resultant crater volume can be used to calculate the quantity of smokeless powder used. The observed TNT equivalent of smokeless powders is estimated from the crater volume results and compared with the calculated TNT equivalent. A reasonable agreement, within experimental error, was found.

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コンクリート板の下に破石が存在する地面に形成されるクレータによる爆発威力評価

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コンクリート板の下に破石が存在する状態の地面に形成されるクレータ体積から爆発の規模を評価することを目的に，C-4と2種類の無煙火薬を用いて，薬量とクレータの大きさの関係，換算爆発高さとコンクリート板の影響を検討した。その結果，コンクリート平板に接触して設置されたC-4(ギャップ長0mm)の場合，見かけのクレータの深さと直径の関係は，様々な岩石，および土質に対する文献値と非常に良く一致すること，換算爆発高さが高くなるとクレータ体積が急激に減少すること，コンクリート平板の有無による影響はちいさいこと，が確認された。一方，無煙火薬の場合，見かけのクレータの深さと直径の関係は，C-4と比較すると，直径はより短く，深さはより深くなること，クレータ体積に対する薬種およびギャップ長の影響は非常に小さいことが明らかになった。C-4および無煙火薬量の実験結果を整理し，見かけのクレータ体積と薬量の実験式を提案した。熱力学平衡計算を実施し，爆轟特性値を算出し，爆発熱の比より無煙火薬のTNT等量の計算値を求めた。これとは別に，クレータ体積から無煙火薬のC-4等量を求め，この値とC-4のTNT等量(計算値)より，無煙火薬のTNT等量の実験値を求めた。両者の比較検討より，計算値と実験値は，概略一致する事が判明した。

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