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Effects of Explosion Energy and Depth to the Formation of Blast Wave and Crater: Field Explosion Experiment for the Understanding of Volcanic Explosion

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Abstract. We made field explosion experiments as an analogue of volcanic explosion to understand the relationship between the explosion condition and the resultant surface phenomena. The main parameters we employed were explosion depth and explosion energy. Through the experiments we confirmed that scaled depth, which is the depth divided by cube root of energy, is the main parameter determining the properties of explosive volcanism. The energy assigned to blast wave decreased exponentially against the scaled depth. The scaled crater diameter became maximum when the scaled depth was about 4×10^{-3} m/J$^{1/3}$.

Scaled crater diameters by nuclear, chemical subsurface and some volcanic explosions were almost the same. From the scaling law, the overpressure at crater rim was estimated to be several MPa, which corresponded to typical rock strength. Probably the ground-forming materials were broken inside the area where overpressure exceeded their strength.

1. Introduction

Many attempts have been made to understand the factors governing the style of volcanic eruption. For example, *Woods and Koyaguchi* [1994] showed that chamber overpressure determined the style of silicic magma eruption - explosive or effusive- by controlling the degree of volatile escape to a permeable conduit wall. Although such models are applicable to steady magmatic eruption, they are insufficient to understand the mechanism of explosive volcanism such as vulcanian and phreatomagmatic eruptions.

It is probable the style of explosive volcanism is controlled by energy and depth of explosion. If we understand their relation, we can infer the condition of the past explosion from geological information, and it might be useful for hazard mitigation. For this reason we made field explosion experiments as an analogue of volcanic explosion. In the present study we focus on how the properties of blast wave and crater diameter change with explosion condition.

2. Observation and experimental condition

In 1996, 1998 and 1999 we carried out the experiments and made a total of 34 shots on pasture in Sobetsu town, Hokkaido, Japan. The main parameters we employed were explosion depth and explosion energy (Table 1). These values produced the scaled depth, which is the depth divided by cube root of energy, between 0 and 0.021 m/J$^{1/3}$. Through the experiments we confirmed that the cube root scaling law (e.g., *Kingery and Pannill,* 1964) was applicable to our experimental results; the observed phenomena changed systematically against the scaled depth.

Although there are some empirical and theoretical studies that reject the applicability of cube root scaling (e.g., *Nordyke* [1962] , *Holsapple and Schmidt* [1980]) we adopt it by two reasons:

1. As will be shown in Chapter 5, compilation of explosion energy - crater diameter data showed that diameter was related well to the energy to the power 1/3, rather than 1/3.4 that was proposed by *Nordyke.*

2. Even if another power law should be theoretically appropriate for scaling, selection of the power (1/3-1/4) is not a serious problem for the present study, because our volcanological interests are, in many cases, approximation of energy and depth, and geological data (and also experimental data) generally do not have enough precision for more precise alalysis.

For explosion we mainly used dynamite whose combustion speed is 3000-7000 m/sec and explosion energy is

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Table 1. List of experimental conditions

	1996[1]			1998					1999				
	E	Di	Di_s	E	De	De_s	Di	Di_s	E	De	De_s	Di	Di_s
E1	0.74	0.24	5.7	3.0	-3.0[2]	-4.5			89.0	2.0	9.7	0.23	1.1
E2	3.0	0.33	5.0	5.9	-3.0[2]	-3.6			89.0	1.2	5.8	1.95	9.4
E3	5.9	0.34	4.1	29.5	-3.0[2]	-21.0			89.0	0.8	3.9	2.70	13.0
E4	29.5	0.62	4.3	20.6	0.0	0.0	0.41	3.2	8.9	0.0	0.0	0.47	4.9
E5	59.0	0.84	4.7	59.0	0.0	0.0	0.07	3.9	89.0[3]	0.8	3.9	2.27	11.0
E6	29.5	0.90	6.3	177.0	0.0	0.0	0.98	3.8	89.0	0.0	0.0	0.52	2.5
E7	3.0	0.45	6.8	120.0	1.0	4.4	2.23	9.7	320.0	1.4	4.4	3.43	10.8
E8	5.9	0.45	5.4	59.0	0.2	1.1	1.45	8.0	8.9	0.4	4.2	0.67	7.0
E9	29.5	0.54	3.8	30.0	0.6	4.2	1.00	6.9	89.0[4]	0.8	3.9	2.30	11.1
E10	79.7	1.06	5.3	442.0	0.0	0.0	1.25	3.5	55.0[4]	1.0	5.7		
E11				29.4	1.2	8.3	0.38	2.6	470.0	0.4	1.1	3.70	10.3
E12				29.4	3.0	21.0	0.0	0.0	89.0	0.4	1.9	2.03	9.8

E: Explosion energy ($\times 10^5$ J), De: Explosion depth (m), De_s: Scaled explosion depth ($\times 10^{-3}$ m/J$^{1/3}$), Di: Crater diameter (m), Di_s: Scaled crater diameter ($\times 10^{-3}$ m/J$^{1/3}$)
[1] All shots were on ground surface; scaled depth was 0 m/J$^{1/3}$ for all shots.
[2] Aerial shots at 3 m high.
[3] An open hole explosion.
[4] Gansaizar shots (E10 did not explode well).

5.9×10^6 J/kg. We also tried another explosive "Gansaizar" whose combustion speed is lower than 300 m/sec and explosion energy is $1.2 - 1.6 \times 10^6$ J/kg (99-E9 and 99-E10, although the latter one failed). When explosion was made at underground condition the holes for installing the explosive were filled with soil. A shot 99-E5 was the only exception that was performed inside the open conduit.

We used piezo pressure sensor (PCB PIEZOTRONICS, INC., Model 137A23) with digital oscilloscope (Nicolet Integra Series Model 20) for blast wave recording, and lead plate blast meter (0.5 mm thick;*Mizushima* [1970], for example) for rough pressure measurements. Their height was fixed to be 1 m. We caliblated the blastmeter using the 1996 records by piezosensor. The dent (d; mm) on the lead plate and the evaluated overpressure (P; kPa) produced the calibration equation

$$P = 20.2d$$

In later section we use this equation to convert the dent into overpressure.

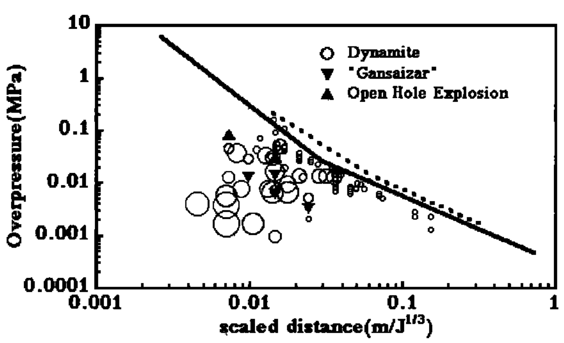

Figure 1. Changes of overpressure against scaled distance. Curves are for ideal explosions compiled by *Kingery and Pannill* [1964] (solid line) and *Baker et al.* [1983] (dotted line). Symbol size corresponds scaled depth of explosion.

3. Blast pressure

The blast overpressure by surface explosions decreased with increasing the scaled distance, and the trend agreed well with the ideal relations by *Kingery and Pannill* [1964] and *Baker et al.* [1983] (Fig. 1). It means the explosion energy mainly converted to the blast energy and the overpressure was a function of the scaled distance from the explosion point.

On the other hand, when the explosion was performed at underground condition, the overpressure decreased not only with increasing the scaled distance but also with increasing the scaled depth. We determined the energy ratio assigned to blast wave by comparing the actual explosion energy with that required producing the same blast pressure by ideal explosion. We found that the energy for blast wave decreased exponentially against scaled depth (Fig. 2). Obviously this resulted because the energy assigned to other phenomena (such as ground destruction) increased with increasing the scaled depth. As mentioned below, the crater diameter, however, became largest when the scaled depth was about 0.004 m/J$^{1/3}$. These imply that the energies assigned to each phenomenon are not simple functions of the scaled depth.

A slow combustion speed explosion using "Gansaizar", and an open hole explosion, both of which seem more appropriate to simulate volcanic explosions, produced almost the same overpressure as that by dynamite explosions at the same scaled depth. This means the overpressure is mainly controlled by scaled depth and scaled distance.

4. Waveform

We observed blast waveforms in 1996 and 1999. All of the 1996 shots were surface or subsurface explosions, and the obtained waveforms were typical of shockwave. As expected from the scaling law their peak pressure and pulse width

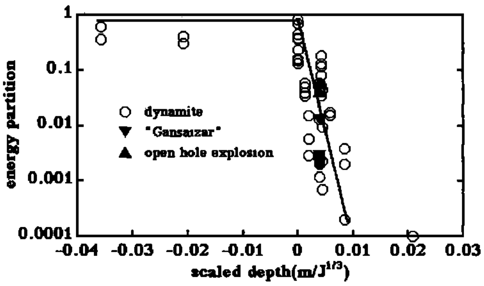

Figure 2. Energy ratio partitioned to blast wave against scaled depth. Large scatter is due to roughness of original lead plate and, in some cases, direct impact by fragment. The value at 0.02 $m/J^{1/3}$ is not an actual one; no blast wave was detected.

became larger with increasing explosion energy; they did not produce new remarkable results that were important to volcanology. Hence we treat the waveform change against the explosion depth using the data in 1999. However they were insufficient for numerical analyses because of clip of data and noise caused by ground motion. For these reasons we focus on the change of waveform with explosion depth.

As shown in Fig. 3, most waveforms by underground explosions (E9, E11 and E12) were shockwave-like and were similar to those by surface explosions (E4 and E6). The most characteristic point was that their pulse width became larger with increasing the explosion depth. For example, the waveform of E12 at 5 m distance had smaller maximum pressure and larger pulse width than those of E6 at 5 m and even at 7 m distances, which were produced by the same energy. The waveform by E12 seemed as if it was the product by a smaller surface explosion. At present we do not have enough data to relate the waveform with depth and energy more precisely. However the present result suggests that the underground explosion is equivalent to the smaller surface explosion as for blast wave formation.

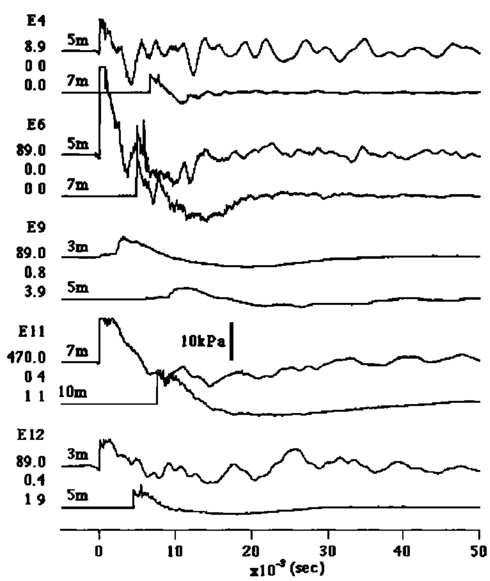

Figure 3. Blast waveforms from 1999 experiments. Noises were due to ground motion and oscillation of the pole which the sensors were placed. Peak pressure of E6-5 m, E11-7 m and E11-10 m were clipped. Notations are in order of experimental number, explosion energy ($\times 10^5$ J), explosion depth (m) and scaled depth ($\times 10^{-3}$ $m/J^{1/3}$). Scales are the same for all waveforms.

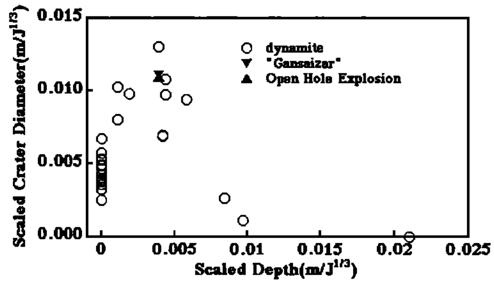

Figure 4. Changes of scaled crater diameter against scaled depth.

5. Crater diameter

The scaled crater diameter increased against scaled depth, became maximum (1.4×10^{-2} $m/J^{1/3}$) when scaled depth was about 4×10^{-3} $m/J^{1/3}$ and then decreased (Fig. 4). This is the same trend as that shown by *Nordyke* [1962] that was analyzed using 1/3.4 scaling.

"Gansaizar" and open hole explosions produced almost the same scaled crater diameter as that by dynamite explosions at the same scaled depth, indicating that the main factor governing the crater diameter is the scaled depth; other parameters such as explosion speed and conduit condition are minor factor.

Sato and Taniguchi [1997] pointed out that logarithmic crater diameter caused by nuclear and chemical subsurface explosions, and also by some volcanic explosions, held the same linear increase against logarithmic energy, although the mode and time duration of explosions differed significantly and the explosion energy ranged in 15 orders of magnitude. Using their data together with those from our experiments and from *Nordyke* [1962] and *Lee and Mazzola* [1989], we obtain the crater diameter (D; m) - explosion energy (E; J) relationship for subsurface artificial explosions (Fig. 5):

$$logD = 0.32logE - 2.06$$

Here we define "subsurface" as the scaled depth shallower than 4×10^{-3} $m/J^{1/3}$. Obviously the data for volcanoes lie on the same trend as those for other explosions, as pointed out by *Sato and Taniguchi*. The slope (0.32) means that the crater diameter - explosion energy relationship follows the cube root scaling law better than 1/3.4 scaling.

The intercept (-2.06) means that the scaled diameter is around 8.7×10^{-3} $m/J^{1/3}$. In our experiments, the scaled crater diameter ranged from 2.5×10^{-3} $m/J^{1/3}$ to 13.0×10^{-3} $m/J^{1/3}$ by surface and subsurface explosions and from 1.1×10^{-3} $m/J^{1/3}$ to 13.0×10^{-3} $m/J^{1/3}$ by deep explosions. Logically it is possible to produce smaller scaled diameter craters by deeper explosions. In volcanic explosions, however, such small scaled crater diameters are improbable because they require quite deep explosions for their energies. In fact, the scaled crater diameters for volcanoes in Fig. 5 range between 3.7×10^{-3} $m/J^{1/3}$ and 10.0×10^{-3} $m/J^{1/3}$. This implies that volcanic explosions plotted in Fig. 5 were almost subsurface phenomena for their explosion energies (cf. Fig. 4), and their crater diameters directly reflect the explosion energy.

The next question is the physical meaning of the scaled crater diameter, 8.7×10^{-3} $m/J^{1/3}$, by subsurface explosions. As for cratering by surface explosions it may be possible to explain the similarity of scaled crater diameter, 2.5-9.8×10^{-3} $m/J^{1/3}$ with average 5.0×10^{-3} $m/J^{1/3}$. To form

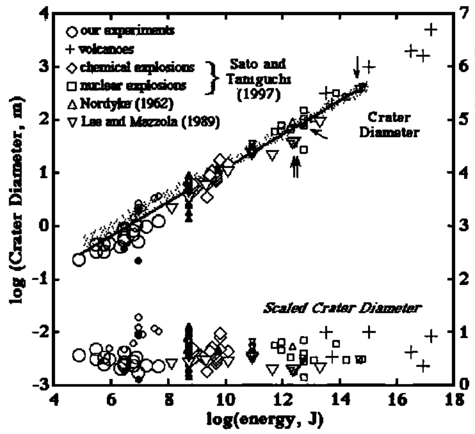

Figure 5. Relationship between explosion energy and formed crater diameter, and resultant scaled crater diameter. Data are from *Lee and Mazzola* [1989], *Nordyke* [1962], *Sato and Taniguchi* [1997] and from our experiments. Open large, open small and solid symbols represent surface, subsurface ($0<De_s<4\times10^{-3}$ m/J$^{1/3}$) and deep (4×10^{-3} m/J$^{1/3}<De_s$) explosions, respectively (symbol for volcano is the exception of this rule, because their scaled depth is unknown). Nuclear explosions in *Lee and Mazzola* [1989] are pointed by arrows. A solid regression line is for surface and subsurface explosions. The expected crater diameter range by *Nordyke* for subsurface explosions is shown by shadow.

a crater, the explosion force has to break rocks and soils. As mentioned previously blast overpressure is a function of scaled distance. The same scaled crater diameter indicates that the blast pressure was the same when it reached the crater rim. If it is possible to extrapolate the pressure - scaled distance relationship by *Kingery and Pannil* [1964] to scaled distance 2.5×10^{-3} m/J$^{1/3}$, the expected overpressure is several MPa, which corresponds to typical shear and tensile rock strength (e.g., *Vutukuri et al.* [1974]). Probably the ground-forming materials are broken inside the area where overpressure exceeds the rock strength. This model is supported by our crater growth experiments (96-E3, E4, E5 and E6). We repeated the explosions at the same point with different energies without filling the existing crater by soil, and found that the crater grew only when the explosion energy was larger than the past ones (E4 and E5). The grown crater diameters agreed with that predicted from each explosion energies. Smaller energy explosions did not grow the existing crater and cumulative energy did not affect the crater diameter (E6), probably because the blast pressure became lower than the rock strength when it reached the crater rim.

It is well known that rock strength decreases with increase in its size to the power -0.1 to -0.5 (e.g., *Vutukuri et al.* [1974]) by including more cracks. As a result rock strength on field scale is smaller than that measured in laboratory. As for cratering, however, the scale effect for rock strength may be negligible, because overpressure decrease faster than the decrease of rock strength against the distance (cf. Fig. 1).

Obviously the above model is not applicable to cratering by underground explosions; the overpressure looses its power when it reaches ground surface. But the rock strength seems to be one of the main factor determining the scaled crater diameter by underground explosions, too, because the power larger than 1/3.4 and the condition $Y > \rho g R$ (Y: strength, ρ: density, g: gravity, R: crater radius) means that the present cratering occurred in the "strength regime" (*Lee and Mazzola* [1989]).

6. Conclusion

The scaled depth is the main parameter determining the properties of volcanic surface phenomena. The underground explosion seemed to be equivalent to the smaller surface explosion as for blast wave formation. The scaled crater diameters showed systematic changes against the scaled depth. Some volcanic explosions whose explosion energy and resultant crater diameter (i.e., scaled crater diameter) were known were almost subsurface phenomena for their explosion energies, and their crater diameters directly reflect the explosion energy.

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