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Modeling is an effective method for studying explosive processes. However, such a complex phenomenon as an explosion often cannot be reproduced on any single model, owing to the qualitative difference between successive phases of development. This circumstance is not infrequently even advantageous. Thus, the modeling of a cratering explosion can be greatly simplified if one confines oneself to consideration of the formation of the crater and the displacement of the ejected rock.

The investigation carried out in work (1) makes it possible to divide the process of formation of a cratering funnel into three stages. In the first stage, beginning from the moment of detonation of the charge, the motion of the surrounding medium is centrally symmetric, as in an unbounded space. The rock, set in motion by the shock wave, is destroyed. Formation of the cavity is completed during the time in which the free surface of the ground rises to a height substantially smaller than the depth at which the charge is emplaced. In the second stage, owing to the energy of the gaseous explosion products in the cavity, a part of the destroyed rock is accelerated in the direction toward the free surface. At the same time a certain fraction of the energy is spent in overcoming the cohesion of the ejected rock with the surrounding massif. The third stage is the inertial flight of the fragmented rock in the field of gravity. The dimensions of the visible crater are determined by the development of the process in the second stage, while the first stage is, as it were, preparatory, providing fragmentation of the rock massif. The kinetic and elastic energy stored by the ejected rock in the first stage is in most cases small in comparison with the energy of the gas in the cavity. Thus, the formation of the crater may be represented as the result of expulsion of fragmented rock by a gas bubble. It should be noted that this process is slow, and therefore the compressibility of the medium may be neglected. The properties of the fragmented rock are determined by the density ρ, the coefficient of internal friction k, and a certain parameter σ, with the dimension of stress, characterizing the connection of the ejected rock with the surrounding massif.

Fig. 1

Figure 1: Fig. 1

The initial conditions are determined by the energy of the gas in the cavity E, the pressure P (or the size of the cavity R_p) and the adiabatic exponent of the gas γ, as well as by the shortest distance w from the center of the cavity to the exposed surface of the massif.

The principal parameter of the crater is its radius R, measured at the level of the free surface (Fig. 1). Since cratering occurs in the field of gravity, it is necessary to include the acceleration of gravity g among the governing parameters.

Starting from the indicated parameters, in accordance with the theory of similarity, one may write the dependence of the crater radius on the initial conditions and the properties of the exploded medium in the form

$$R/w = F_1(E/\rho g w^4;\ E/\sigma w^3;\ R_\text{p}/w;\ \gamma;\ k)$$

or

$$R/w = F_2(P/\rho g w;\ P/\sigma;\ R_\text{p}/w;\ \gamma;\ k). \tag{1}$$

From relations (1) it follows that a large explosion can be modeled either by creating a strong acceleration field, or by correspondingly reducing P and σ, so that the dimensionless parameters in nature and in the model are identical.

The number of parameters can be reduced if one takes into account that the work against cohesion forces and the energy of lifting in the gravitational field must, in essence, be added together. Hence we obtain

Fig. 1

$$\frac{R}{w} = F_1\left(\frac{E}{\rho g w^4 + \sigma w^3}; \frac{R}{w}; \gamma; k\right). \tag{2}$$

The parameter σ can be determined either by comparing explosions of different scale that produce similar craters ($R/w = \text{const}$), or in small-scale experiments, when it is possible to measure the cavity radius and compute the energy E from the known adiabat of the explosion products.

To test the modeling method set forth above, an experimental study was made of the dependence of the crater radius on the principal arguments $E/(\rho g w^4 + \sigma w^3)$ and $R\,/w$. Dry sand was used as the medium; for it $\sigma \approx 0$. We note that the absence of cohesion in sand does not at all mean that the energy expenditure for overcoming cohesive forces is also zero. The frictional forces arising in the process of extrusion of the sand by the gas bubble will necessarily

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

lead to dissipation of energy, but, as is readily seen, this is taken into account by the introduction of the dimensionless parameter k.

The experiments were carried out in an evacuated cylindrical chamber 500 mm in diameter and 500 mm long. A layer of dry sand of density $\rho = 1.5$ g/cm^3 had a thickness of about 250 mm. Inside the layer, at a specified depth w, a spherical air bubble enclosed in a thin rubber shell was placed. Rupture of the shell was effected by a heated nichrome wire in contact with the shell. The time of rupture of the shell was much shorter than the time of development of the throw-out. The released air bubble, expanding, pushed out the sand lying above it, forming a crater.

Fig. 2

Four series of experiments were carried out, in each of which $R\,/w$ was fixed (0.22; 0.31; 0.42; 0.63), and the pressure in the bubble was varied from 0.05 to 0.5 kgf/cm^2. The gas energy was calculated from the formula $E = 4\pi R^3 P/3(\gamma - 1)$. Since the chamber was not evacuated completely (the residual pressure was ~ 0.01 of the pressure in the bubble), a correction was introduced in processing the experimental results: to the weight of the sand was added the residual atmospheric pressure $\rho g w + P_0$. The experimental results are presented in Fig. 2 in the coordinates R/w, $\lg E/(\rho g w^4 + P_0 w^3)$, where a denotes experimental data for $R\,/w = 0.22$, for $R\,/w = 0.31$, for $R\,/w = 0.42$, and for $R\,/w = 0.63$. It is interesting to note that over a fairly wide range of variation, $0.22 \leq R\,/w \leq 0.63$, when the volume of the bubble changed by more than an order of magnitude, the crater radius does not depend on the parameter $R\,/w$.

Figure 3 shows motion-picture frames of a model "explosion" for throw-out ($E = 1.7 \cdot 10^8$ erg, $w = 10.5$ cm).

Fig. 3. Time from the moment of explosion: a –31 msec, b –62 msec, v –93 msec, g –124 msec, d –155 msec, e –186 msec, zh –217 msec, z –248 msec.

Let us give an example of comparing the results of laboratory modeling with the published (2) data on the "Scooter" explosion. The cratering explosion known as "Scooter" was carried out at a depth of 38 m in alluvium. For this explosion one may estimate the energy of the gas in the cavity at the moment of completion of the first stage. It is approximately $4.8 \cdot 10^{18}$ erg. Since alluvium is a weakly cemented fine-grained medium, the quantity σ may be neglected in comparison with $\rho g w$. The "Scooter" explosion corresponds to point d in Fig. 2.

Let us also compare the maximum velocities of rise of the dome of ejected ground. The velocities in the model and in the full-scale case, in accordance with the Froude criterion, should be related as the square root of the ratio of the linear dimensions. In the model experiment that had the same cratering index R/w as the "Scooter" explosion, a velocity of 2.4 m/sec was recorded. Conversion to the full-scale case gives 45 m/sec. The measured maximum velocity of ground rise in the "Scooter" explosion is $\sim$ 40 m/sec.

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Note: Figure translations are in progress. See original paper for figures.