THE THERMOPHYSICAL PROPERTIES OF THE MEDIUM AT THE CENTER OF AN ELECTRICAL EXPLOSION IN RELATION TO THE PARAMETERS OF THE CRATER

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An attempt is made to compare electrical and chemical cratering explosions in dry loose sand and estimate the effect of the thermophysical properties of the medium in the vicinity of the electrical explosion center on the parameters of the crater.

As shown in [1], the introduction of easily volatilized material into the focal zone of an electrical explosion increases the intensity of the compression wave; however, as follows from the theory of development of a cratering explosion [2, 3], the results relating to an underground explosion cannot be automatically transferred to the case of ejection and the questions involved require special consideration.

We have obtained experimental relations for the ejection coefficient, the crater volume per unit explosion energy, and the ratio of crater depth to explosion depth as a function of the reduced depth of the explosion source. It has been shown that the size of the crater depends importantly on the thermophysical properties of the material in the explosion zone. For the investigated types of explosions it is possible to give a value of the TNT equivalent ensuring similarity of the explosions in terms of energy with respect to all the parameters characterizing the crater.

Organization of the experiment. As explosion sources we used a powerful electrical discharge and spherical explosive charges (PETN). The experiments were conducted in a tank measuring 1.2 × 1.2 m^2 filled with dry sand of density 1.55 g/cm^3. The distance from the center of the explosion to the bottom of the tank was 170 mm, which exceeded by a factor of 2.5 the maximum depth of the explosion source during the experiments.

The electrical discharge was triggered at the end of a coaxial discharger 16 mm in diameter (1 in Fig. 1). The energy released, which was measured in each experiment by oscillographing the current and voltage across the discharge gap, fluctuated slightly, about 8 kJ from experiment to experiment. In the electrical explosion the energy was released in about 50 μsec. In control experiments to measure the mass velocity in the compression wave produced by a noncratering electrical explosion in sand [4] it was established, by comparison with analogous data on electrical explosions on a half-space [5], that the discharger employed does not distort the motion of the soil in the direction of the free surface: the compression-wave parameters correspond to the energy released.

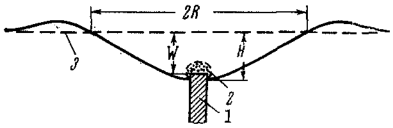

Fig. 1

In order to ensure better comparability with the results of electrical explosions, the PETN charges were attached to a metal rod that simulated the coaxial discharger. The pressed charges weighed 0.8 g. The charges were initiated by passing an electrical pulse through a wire inserted in the charge.

In the experiments crater profiles were directly recorded in two mutually perpendicular directions and then used to construct the average profile. The difference between the linear dimensions of the average profile and the two recorded profiles did not exceed 5%.

For recording the crater profile we used a simple method that ensured accurate results despite the small scale of the explosions. After the explosion, a thin (1 mm) Dural sheet with millimeter graph paper glued to it was inserted into the sand along special vertical guides, the plane of the sheet passing through the explosion center. The paper, on which the position of the free surface (3 in Fig. 1) had previously been marked, was then sprayed with paint. The contour of the colored portion then represented the crater profile. The error in calculating the linear dimensions by this method was not more than 1–2 mm.

The principal measured parameters (see Fig. 1) were R, the crater radius measured at the level of the free surface; H, the crater depth; and V, the crater volume, which was computed as the volume of the body formed by rotating the average crater profile about the vertical axis.

Experimental Results. In Fig. 2 the dependence of $n = R/W$ on the reduced depth of the explosions source $W/C^{1/3}$ is shown on a log-log scale. Here, R and W are measured in meters, and C is the weight in kg of the TNT equivalent in energy to the electrical or chemical explosion. Curve 1 in Fig. 2 corresponds to electrical explosion, curve 2 to the explosion of charges of PETN. A logarithmic scale was introduced along the axis of abscissas in order to demonstrate graphically the possibility of introducing a TNT equivalent.

In Fig. 3 electrical and chemical explosions are compared with respect to crater volume per unit explosion energy V/C as a function of the reduced depth. Here, the volume V is measured in m^3, while the remaining units and notation are the same as in Fig. 2.

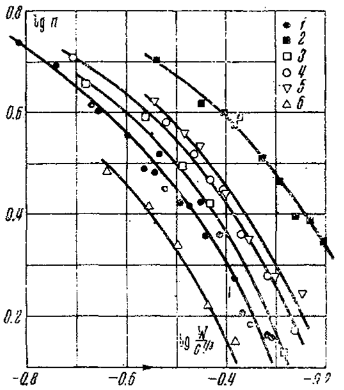

Fig. 2

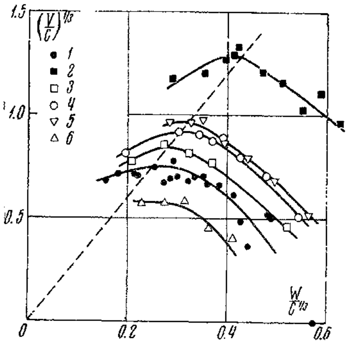

Fig. 3

It is clear from these two figures that a cratering electrical explosion is much less effective than a chemical explosion of the same energy. The TNT equivalent for an electrical explosion with respect to the ejection coefficient is equal to 0.21. An estimate of the TNT equivalent from the dependence of the ratio V/C on the reduced depth, restricted for the sake of simplicity to a single point – the maximum – gives a value 0.18, which is very close to the TNT equivalent for the ejection coefficient. The relative efficiencies of the explosions with respect to other crater parameters are compared below.

It is one of the principal distinguishing features of the electrical explosion that there are practically no direct explosion products. When energy is released in the discharge gap, apart from high-temperature plasma, only the evaporation products of the surrounding medium are formed. Obviously, the properties of the material in the vicinity of the explosion center will determine the composition, quantity and energy of the gaseous products. Thus, the efficiency of energy transmission to the surrounding medium, and hence the crater parameters, will vary with the nature of the material in the immediate vicinity of the discharge gap.

For purposes of investigation we selected copper sulfate $CuSO_4 \cdot 5H_2O$, zinc carbonate $ZnCO_3$, iodine, and boron carbide B_4C.

All these substances were introduced into the explosion zone in the form of weighed amounts of finely crystalline powder (2 in Fig. 1), which were given, as nearly as possible, a spherical shape. The small volume of material introduced (radius not greater than 15 mm) and the approximate equivalence of its bulk density and granulometric composition and those of the sand indicate that the mechanical properties of the medium in the immediate vicinity of the discharger remained practically the same, and hence that the observed effects were determined by the changes in the thermophysical properties of the material at the explosion center. This assumption was checked by means of control experiments, in which chemical charges surrounded by weighed amounts of copper sulfate and iodine were used to produce noncratering explosions. The results of these experiments (maximum mass velocity) did not differ from the results of a chemical explosion in pure sand.

The question of the effect of water at the explosion center on the ejection effect is of some practical importance. Water may occur in soils both in the unbound state and in the form of water of crystallization, which is relatively easily freed when the crystal hydrate is heated.

Copper sulfate is a crystal hydrate that loses all its water at 150° C. The compound contains 36% water of crystallization, and the binding energy is equal to 284 cal/g compound.

At first, we investigated the dependence of the crater volume on the weight of copper sulfate. The results of these experiments are presented in Fig. 4, where along the ordinate axis we have plotted the ratio of the crater volume for an electrical explosion in the presence of $CuSO_4 \cdot 5H_2O$ to the crater volume in the presence of pure sand, and along the axis of abscissas the weight of copper sulfate in grams. All the experiments were conducted at the same explosion energy ≈ 8.8 kJ and at a fixed discharger depth $W = 39$ mm. This depth ($W/C^{1/3} = 0.305$), at which a slight change in W has almost no effect on the crater volume, was not selected arbitrarily, but in order to avoid a change in crater volume as a result of minor fluctuations in explosion energy. The dependence in Fig. 4 shows that, starting at about 5 g, further increase in the weight of copper sulfate does not cause any appreciable increase in the effect. This figure is consistent with the result of a simple estimate, which shows that the electrical explosion energy is sufficient to detach the water of crystallization from 7.4 g of copper sulfate.

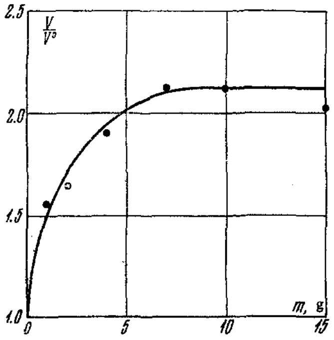

Fig. 4

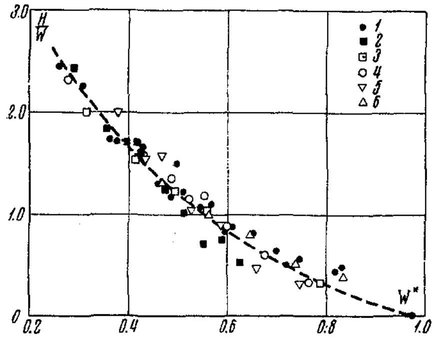

Fig. 5

Also, the presence of "saturation" in Fig. 4 is additional confirmation of our assumption concerning the relative constancy of the mechanical properties of the medium when the investigated materials are introduced.

In accordance with the results obtained, in the subsequent experiments we used 10 g of copper sulfate. The results of these experiments are represented by curves 4 in Figs. 2 and 3. It is clear from these figures that in the presence of copper sulfate the efficiency of the electrical explosion increased appreciably: by a factor of 1.7 with respect to the ejection coefficient and by a factor of 2.0 with respect to maximum crater volume per unit energy.

Carbonates are another example of relatively unstable compounds, rather frequently encountered in nature (limestone, magnesite, dolomite, etc.). When heated, carbonates decompose into metal oxides and carbon dioxide.

For the purposes of these experiments we selected zinc carbonate, since it has the least energy (16 kcal/mole) and lowest dissociation temperature (300° C at atmospheric pressure) of the common carbonates. The results of the experiments conducted with 5 g of zinc carbonate in the vicinity of the explosion center are represented by curves 3 in Figs. 2 and 3. An analysis of the results shows that the efficiency of the electrical explosion increased by a factor of 1.4 with respect to the ejection coefficient and 1.6 with respect to the maximum value of V/C.

Similar experiments were conducted with crystalline iodine. The weight of iodine (6 g) was selected on the basis of the results of [1]. The data of the iodine experiments are represented by curves 5 in Figs. 2 and 3. The efficiency of the electrical explosion is increased by a factor of 2.1 with respect to the ejection coefficient and by a factor of 2.3 with respect to the maximum value of V/C.

The above substances (as in [1]) form gaseous products at lower temperatures and with smaller expenditure of energy than quartz sand; therefore, from the qualitative standpoint, an increase in the efficiency of explosion energy utilization when such substances are introduced is understandable. We accordingly decided to pursue this trend by experimenting with substances possessing a higher boiling point and higher heat of vaporization than sand.

As such a substance we selected boron carbide (boiling point higher than 3500° C). The results of the experiments with 17 g of boron carbide are described by curves 6 in Figs. 2 and 3. As was to be expected, the efficiency of the explosion decreased (by a factor of 1.75 with respect to the ejection coefficient, and by a factor of approximately 1.9 with respect to the maximum value of V/C).

We will now consider whether energy similarity exists between an electrical explosion in pure sand, an electrical explosion in the presence of various foreign materials, and a chemical explosion with respect to other parameters characterizing the crater, concluding with a brief discussion of the results.

The curves in Figs. 5 and 6 represent the dependence of the ratio H/W and the quantity $V^* = V/(\eta C)^{1/3}$ on the reduced depth of the explosion source $W^* = W/(\eta C)^{1/3}$; here, η is the TNT equivalent based on the ejection coefficient; for an electrical explosion in pure sand $\eta = 0.21$, in copper sulfate $\eta = 0.36$, in zinc carbonate $\eta = 0.29$, in iodine $\eta = 0.43$, and in boron carbide $\eta = 0.12$. The notation in the two figures is the same as in Figs. 2 and 3. Clearly, there is a satisfactory similarity between all the types of explosions in question with respect to the other parameters characterizing the crater, the value of the TNT equivalent for all the parameters remaining constant.

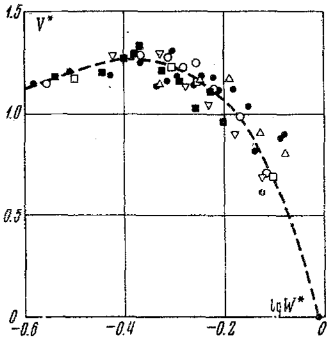

Fig. 6

As may be seen from Fig. 3, in all cases (except for the experiments with boron carbide, in a small number of which the interval of variation of the reduced depth was not sufficiently broad) the V/C dependence has a maximum. The decrease in crater volume at small depths of the explosion source is due to the inefficient utilization of the energy of the explosion products, which under these conditions burst into the atmosphere through the thin layer of sand. The maximum crater volume per unit explosion energy is reached at almost the same ejection coefficient $n \approx 3.6$ and the same reduced depth $W^* \approx 0.42$ m/kg$^{1/3}$.

In the presence of energy similarity between the types of explosions considered, the maxima of all the curves in Fig. 3 should lie on the same straight line through the coordinate origin. As follows from Fig. 3, this a quite accurate representation of the facts.

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