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L. V. AL' TSHULER, A. V. BALABANOV, V. A. BATALOV, N. A. GERASHCHENKO,
V. A. RODIONOV, V. A. SVIDINSKII, D. M. TARASOV

CAMOUFLET EXPLOSION IN LIQUID AND ELASTOPLASTIC MEDIA

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The explosion of spherical charges in soils causes the expansion of a camouflet cavity and the motion of the surrounding medium, which decays as a result of its plastic and elastic resistance. A qualitative mathematical description of the phenomenon in the linear approximation and in the approximation of incompressible and porous-incompressible media has been given in a number of Soviet ($^{1-8}$) and foreign (^{9,10}) publications. The experimental development of camouflet cavities in sand has been studied in (^{7,8,11}).

In the present communication we briefly set forth the results of an experimental and mathematical investigation of camouflet explosions in water, an aqueous $ZnCl_2$ solution ($\rho_c = 2$ g/cm^3), wet clay, aluminum, hardened cement-sand mortar, and rock salt. To interpret the experimental results, we used the results of numerical calculations of elastoplastic flows carried out with a program having much in common with Wilkins' method (^{12}).

The properties of the medium were described by equations of state in the form

$$P = P_x(\sigma) + \rho_0 \sigma \Gamma [E - E_x(\sigma)], \tag{1}$$

supplemented by the plasticity conditions

$$P_r - P_\theta = k + m(\sigma - 1)/\sigma. \tag{2}$$

In (1) and (2), $P = \frac{1}{3}(P_r + 2P_\theta)$ is the pressure; P_r, P_θ are the radial and tangential compressive stresses; $P_x = \frac{\rho_0 c_0^2}{n}(\sigma^n - 1)$ is the "cold" resistance of the medium; ρ_0 is the initial density; c_0 is the initial speed of sound; $\sigma = \rho/\rho_0$ is the degree of compression; $E_x = \int_1^\sigma \frac{c_0^2}{n}(\sigma^n - 1)\frac{d\sigma}{\sigma^2}$ is the energy of "cold" compression; E is the specific internal energy; Γ is the Grüneisen coefficient; k is the constant of plastic resistance at $P = 0$; m is the coefficient of strengthening by pressure.

Fig. 1

Figure 1: Fig. 1

Table 1

Medium	ρ_0, g/cm^3	c_0, km/s	n	Γ	k_{st}, kT/cm^2	r_{03}, mm	a_0, mm	ρ_{ev}, g/m^3	P_α, kbar
Water	1	1.5	6	1	–	9	9	1.58	75
$ZnCl_2$ solution	2	1.64	6.5	0.8	–	9	9	1.58	75
Wet clay	2	2.1	5.33	0.57	–	9	8	1.58	75
Aluminum	2.77	5.5	3.5	0.9	7	17.5	18	1.515	65
Cement-sand mortar	2.03	1.64	5	0.4	1.45	9	10	1.215	35
NaCl	2.16	3.4	3.75	1	2-3	–	–	–	–

The parameters of the equations of state of the materials studied are given in the left-hand part of Table 1; the value of the static strength k_{st} is also given there.

In selecting the equations of state, data on the dynamic compression of the substances investigated and on their compressibility under normal conditions were used. The behavior of the detonation products of charges made of a 50% alloy of TNT and hexogen was described by the isentrope equation

$$P = 11.61\rho^{11/3} + 8.480\rho^{4/3}. \tag{3}$$

Equation (3) is an interpretation of the data published in (^{13}). Here ρ is given in g/cm^3 and P in kbar.

Experimental observation of the development of camouflet cavities was carried out by methods of pulsed radiography. Short radiation pulses were generated by an X-ray tube with a needle anode (^{14}) and, in a number of experiments, by an iron-free betatron (^{15}). In the first case the nominal voltage of the pulse generator was ~ 3.5 MV, and in the second the maximum electron energy reached 70 MeV.

Fig. 1

Fig. 2

Fig. 2

Figure 2: Fig. 2

Fig. 3 and Fig. 4

Figure 3: Fig. 3 and Fig. 4

Fig. 1. r—t diagram of cavity expansion during an explosion in water

Fig. 2. r—t diagram of cavity expansion during an explosion in clay (a), $ZnCl_2$ solution (b), and water (c)

Charges of radius 9 and 17.5 mm were placed at the center of cubic blocks with an edge length of 200 mm or of spherical containers of the same diameter. Most of the experiments, including all records of the later phases of the phenomenon, were carried out with charges having $r_{0\mathrm{z}} = 9$ mm in order to avoid the influence of rarefaction waves from the outer surface. For liquid and plastic media the charge radius $r_{0\mathrm{z}}$ and the initial cavity radius a_0 coincided. For aluminum and cement-sand mortar they differed somewhat.

The charge dimensions, the initial dimensions of the cavities, the average densities of the explosive, and the corresponding initial pressures are given in the right-hand part of Table 1.

The results of experiment and calculation are presented in diagrams of relative radius $\tilde{r}$ versus relative time $\tilde{t}$ (Figs. 1-3). The initial cavity radius a_0 was taken as the unit of length; the unit of time was $t_0 = a_0/u_0$ at $u_0 = 1$ km/s (numerically, t_0 in μsec is equal to the length a in mm). The cavity develops fastest in water and somewhat more slowly in clay and in an aqueous $ZnCl_2$ solution. For the latter two substances, which have similar initial densities and similar equations of state, the expansion curves almost coincide (Fig. 2). In aluminum, the initial phase of motion and the final cavity size r_{k}, 1.9 times greater than the initial one, were recorded experimentally. For cement-sand blocks, $\tilde{r}_{\mathrm{k}} = 2.6a_0$.

Calculations without taking into account the shear strength of the medium approximate well the experimental curves for water, an aqueous solution of $ZnCl_2$, wet clay, as well as the initial phases of motion of solid media. For the latter, agreement with experiment in the final segment of the trajectory is achieved by introducing into the calculation program constants of plastic resistance to shear. For aluminum the best agreement of the calculation with experiment occurs at $k = 11.9$ kgf/mm^2 and depends very little on m; for cement-sand mortar, at $k = 3.4$ kgf/mm^2. These quantities, which determine the effective dynamic resistance of solids, substantially exceed the static strength limits (see Table 1).

Fig. 3. r—t diagram of cavity expansion during an explosion: 1—3, in aluminum at $\sigma_s = 13.0$ kgf/mm^2 (1), 11.9 kgf/mm^2 (2), and 10.0 kgf/mm^2 (3);

4—5, in cement-sand mortar at $\sigma = 4.0$ kgf/mm^2 (4), 3.4 kgf/mm^2 (5), and 1.45 kgf/mm^2 (6)

Fig. 4. r—t diagram of cavity expansion during an explosion in NaCl at $\sigma_s = 340$ kgf/cm^2 (1), 100 kgf/cm^2 (2), and 50 kgf/cm^2 (3). Lithostatic pressure 200 atm.

To clarify the role of confining pressure, the authors carried out calculations of contained explosions in media differing in strength at a confining pressure of 200 atm. The results of the computations, performed with the NaCl equation of state, are presented graphically in Fig. 4. The unit of length in these graphs is the dynamic radius

$$r_d = \sqrt[3]{Q/\rho_0 c_0^2}$$

(Q is the charge energy), and the unit of time is $t_0 = r_d/c_0$. The calculated curves correspond to the values $k = 50;\ 100;\ 340$ kgf/cm^2 and $m = 0$.

As is seen from the $\tilde{r}$—$\tilde{t}$ diagrams, one and the same final value of the cavity radius can be obtained in media of different strength with the same explosion energy.

The mathematical method developed, as shown by comparison of calculations and experiment, describes with good accuracy the phenomenon of a contained explosion in liquid and elastic-plastic media. Its application makes it possible to analyze the influence, on the process of cavity formation, of the equation of state of the detonation products and of the principal parameters of the medium —density, compressibility, strength, and confining pressure.

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