CYLINDRICAL DETONATION WAVES IN MULTICOMPONENT MEDIA

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UDC 534.222

The problem of the applicability of the model [1] to water-saturated soils has been discussed in [2, 3]. Problems are solved in [4-7] with the use of this model. Dependences on distance at the shock front, as well as the variation of these parameters with time at fixed points of the medium, are determined in this paper. A comparison conducted of the obtained data with experimental results indicates the applicability to soils of the model of a multicomponent medium.

§1. The soil is assumed to be a three-component medium whose deformation is determined by the compressibility of air, water, and the solid component. According to the model [1] of a multicomponent medium, deformations occur instantaneously at the instant of load application; the equation of compression and unloading has the form

$$\frac{\rho_0}{\rho}=\alpha_1\left(\frac{p}{p_0}\right)^{-\varkappa_1}+\alpha_2\left[\frac{\gamma_2(p-p_0)}{\rho_2c_2^2}+1\right]^{-\varkappa_2}+\alpha_3\left[\frac{\gamma_3(p-p_0)}{\rho_3c_3^2}+1\right]^{-\varkappa_3} \quad (1.1)$$

$$(\varkappa_1=1/\gamma_1,\ \varkappa_2=1/\gamma_2,\ \varkappa_3=1/\gamma_3),$$

where α_1, α_2, and α_3 are the volume content of gaseous, liquid, and solid components in the medium; ρ_1, ρ_2, and ρ_3 are the densities; c_1, c_2, and c_3 are the velocities and γ_1, γ_2, and γ_3 are the isentrope coefficients in these components at the pressure $p=p_0$; and ρ_0 and ρ are the natural and instantaneous densities of the medium, respectively.

Detonation of the charge is assumed to be instantaneous, i.e., the wave pattern in the cavity is not considered. Just as in [2, 8], the isentrope equations of the detonation products (DP) has the form

$$p=A\rho_{\mathrm{DP}}^{n}+B\rho_{\mathrm{DP}}^{\gamma+1}. \quad (1.2)$$

This equation changes to the equations

$$p=p_n(\rho_{\mathrm{DP}}/\rho_n)^{k_n},\ p=p_0(\rho_{\mathrm{DP}}/\rho_0)^{k_0}. \quad (1.3)$$

in the case of large and small pressures, respectively.

A system of four equations is set up for the determination of the quantities A, B, n, and γ which are derived from the following conditions: The first of Eqs. (1.3) and Eq. (1.2) have a common point p_n, ρ_n and a common tangent at this point, and as $\rho\to 0$, Eq. (1.2) and the second of Eqs. (1.3) have a common tangent; upon the expansion from p_n, ρ_n the detonation products perform work equal to the heat of explosive transformation,

$$A\rho_n^n+B\rho_n^{\gamma+1}=p_n,\ k_n=n+\frac{B\rho_n^{\gamma+1}}{p_n}(\gamma+1-n), \quad (1.4)$$

$$\gamma=k_0-1,\ Q=\frac{p_n}{\rho_n(n-1)}+\frac{B\rho_n^{\gamma}}{\gamma(n-1)}(n-\gamma-1).$$

The equations of motion of the soil have the form

$$\frac{\partial V}{\partial t}-\frac{1}{\rho_0}\frac{R}{r}\frac{\partial u}{\partial r}-\frac{u}{r}=0,\ \frac{\partial u}{\partial t}+\frac{1}{\rho_0}\frac{R}{r}\frac{\partial p}{\partial r}=0,\ u=\frac{\partial R}{\partial t},\ V=1/\rho \quad (1.5)$$

in Lagrangian variables, where R and r are the Eulerian and Lagrangian coordinates, respectively, t is the time, and u is the velocity of a soil particle.

Kiev. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 93-99, May-June, 1978. Original article submitted April 28, 1977.

 0021-8944/78/1903-0356$07.50

TABLE 1

Medium No.	α_1	α_2	α_3
1	0	0,4	0,6
2	0,02	0,38	0,6
3	0,04	0,36	0,6
4	0,10	0,30	0,6
5	0	1	0

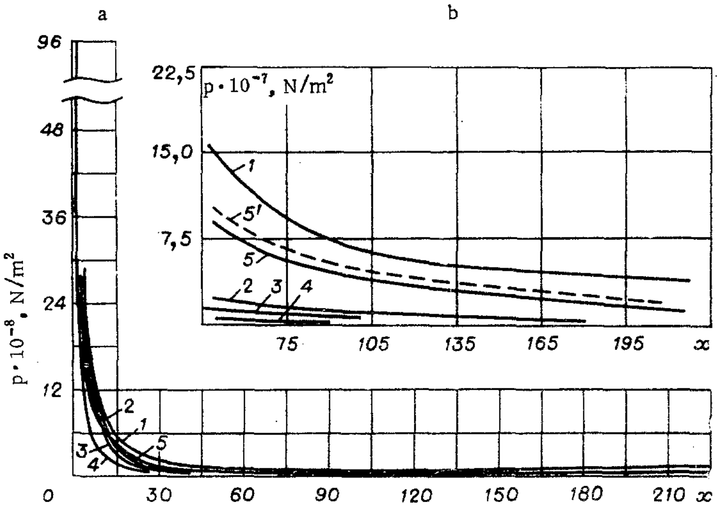

Fig. 1

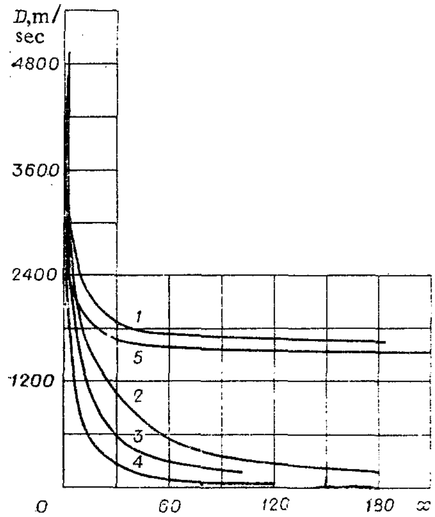

Fig. 2

The system (1.5) has two families of characteristics:

$$\frac{dp}{\rho c} \pm du + \frac{uc}{R}\, dt = 0 \quad \text{for} \quad dr = \frac{c\rho}{\rho_0} \frac{R}{r}\, dt.$$

Equations (1.1) and (1.5) represent a closed system. The boundary conditions are the conditions at the shock front S and the condition at the detonation products–soil boundary (at the contact explosion T for $r = r_0$, where r_0 is the charge radius):

$$p - p_0 = \rho_0 u D,\ \rho u = (\rho - \rho_0) D,\ \rho_{DP} / \rho_n = (r_0/R)^2, \tag{1.6}$$

where D is the velocity of the shock front.

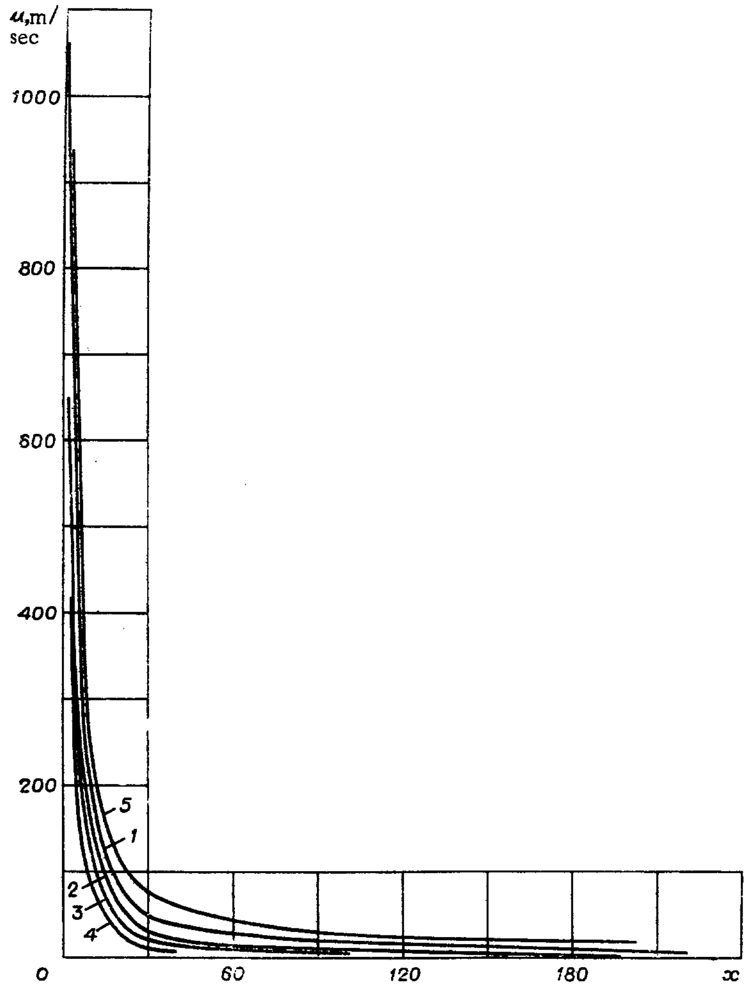

Fig. 3

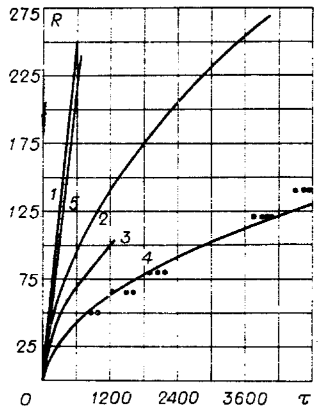

Fig. 4

It is more convenient to perform the calculation in dimensionless quantities and variables. The conversion to them is accomplished according to the equations

$$p^0 = p/p_n,\ u^0 = u/c_n,\ D^0 = D/c_n,\ \rho^0 = \rho/\rho_n, \qquad (1.7)$$
$$R^0 = R/r_0,\ x = r/r_0,\ \tau = tc_n/r_0.$$

The characteristic relationships are written as follows in the dimensionless variables:

$$\frac{dp^0}{k_n \rho^0 c^0} \pm du^0 + \frac{u^0 c^0}{R^0}\, d\tau = 0 \ \text{for} \quad dx = \pm \frac{c^0 \rho^0}{\rho_0^0} \frac{R^0}{x}\, d\tau.$$

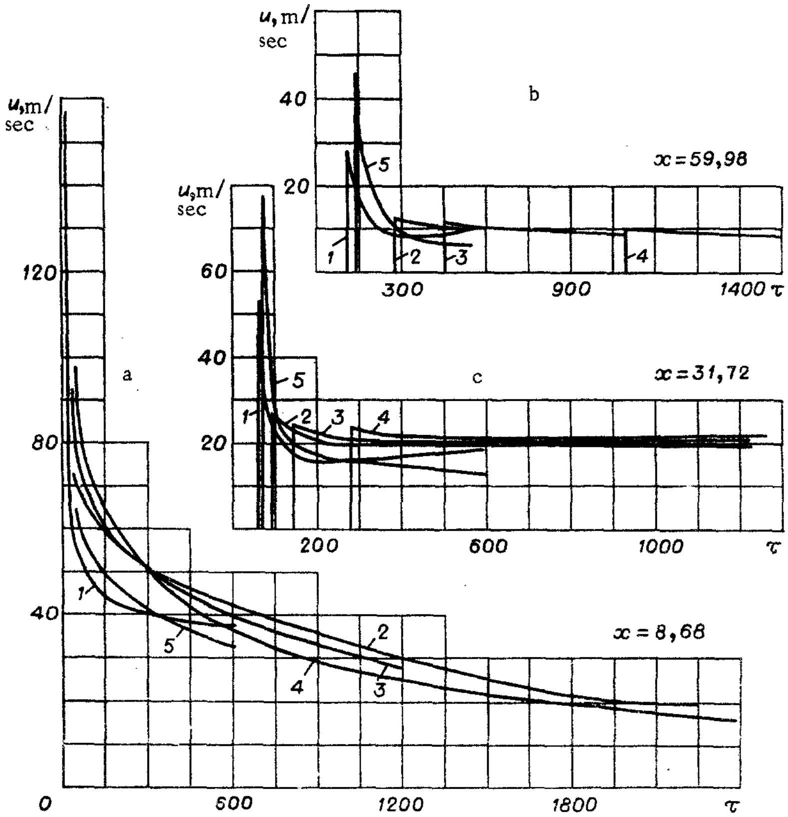

Fig. 5

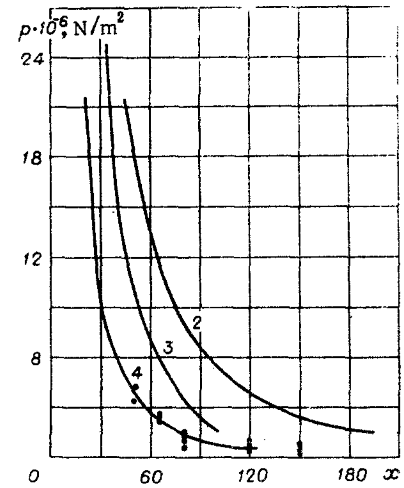

Fig. 6

The equation of state of the three-component medium is

$$\frac{\rho_0^0}{\rho^0} = \alpha_1 \left(\frac{p^0}{p_0^0}\right)^{-\varkappa_1} + \alpha_2 \left[\frac{\gamma_2 (p^0 - p_0^0)}{k_n \rho_2^0 c_2^{02}} + 1\right]^{-\varkappa_2} + \alpha_3 \left[\frac{\gamma_3 (p^0 - p_0^0)}{k_n \rho_3^0 c_3^{02}} + 1\right]^{-\varkappa_3}$$

in dimensionless form. The isentrope equation (1.2) has the form

$$p^0 = A^0 (\rho^0_{\mathrm{DP}})^n + B^0 (\rho^0_{\mathrm{DP}})^{\gamma+1}, \quad A^0 = A\rho_n^n/p_n, \quad B^0 = B\rho_n^{\gamma+1}/p_n$$

in the new variables. The quantities A^0, B^0, n, and γ are determined from equations which are derived from (1.2) and (1.4):

$$A^0 + B^0 = 1,\ k_n = n + B^0(\gamma - n + 1),\ \gamma = k_0 - 1,\ Q^0 = \frac{Q\rho_n}{p_n} = \\ = \frac{1}{n-1} + \frac{B^0}{\gamma(n-1)}(n - \gamma - 1).$$

The boundary conditions (1.6) with (1.7) taken into account are modified to the form

$$\rho^0_{DP} = (R^0)^{-2} \quad \text{at} \quad x = 1,\ p^0 - p^0_0 = k_n\rho^0_0 D^0 u^0,\ \rho^0 u^0 = (\rho^0 - \rho^0_0)\,D^0.$$

The problem has been solved for four types of water-saturated soils and water and for explosives of the Trotyl type.

The parameters characterizing the properties of the explosives have the values $k_n = 3$, $k_0 = 1.25$, $p_n = 96 \cdot 10^8$ N/m^2, $\rho_n = 1600$ kg/m^3, and $Q = 4.19 \cdot 10^6$ J/kg. The soils have the identical porosity $\alpha_1 + \alpha_2 = 0.4$.

The characteristics of the soil components have the values

$$\rho_1 = 1.20\,\text{kg/m}^3,\ \rho_2 = 1000\,\text{kg/m}^3,\ \rho_3 = 2650\,\text{kg/m}^3,$$
$$c_1 = 330\,\text{m/sec},\ c_2 = 1500\ \text{m/sec},\ c_3 = 4500\ \text{m/sec},\ \gamma_1 = 1.4,\ \gamma_2 = 7,\ \gamma_3 = 4.$$

The content of the components in the soils treated is given in Table 1.

It is necessary to consider three types of points in this problem: at the shock front S, in the medium between the front S and the contact explosion T, and at the contact explosion T. Each of these types of points has its own computational algorithm.

The step in the spatial coordinate Δx remained constant during the solution; its value is determined by the required accuracy of the solution. The time step $\Delta\tau$ was varied from layer to layer in agreement with Hartree's scheme [9] in the following way:

$$\Delta\tau_i = 2\Delta x/(D_{i-1} + D_i),$$

where i is the index of the temporal step and D_i and D_{i-1} are the velocity of the front at the i-th and (i−1)-th steps.

The order of the calculation of the parameters for all types of points was chosen just as in [4]. The number of iterations in the calculation was determined by the required accuracy (the computational accuracy amounted to 0.01 kgf/cm^2 for the pressure).

§ 2. The numbering of the curves in Figs. 1-6 corresponds to the numbering of the media in Table 1. Plots of the variation of pressure with distance are given in Fig. 1, where it is evident that the pressure drops off most strongly in the region $x \leq 15$ from $96 \cdot 10^8$ to $4 \cdot 10^8$ N/m^2 (for the first medium) and to $4 \cdot 10^7$ N/m^2 (for the fourth medium). As α_1 increases, the attenuation of the pressure wave with distance also increases. At the same time the pressure ratio p_1/p_4 (the subscripts correspond to the medium number) increases from 1 to 10 in the region $x \leq 15$, and this ratio is larger than 50 in the region $x \geq 60$ (see Fig. 1b). Pressure attenuation occurs more rapidly in water than in soil with $\alpha_1 = 0$ and more slowly than in soils with $\alpha_1 \neq 0$. Curve 5' corresponds to explosions of cylindrical charges in water [8].

The velocity of the front (Fig. 2) drops off most strongly with distance in all media in the region $x \leq 15$, just as does the pressure; at the same time the rate of the velocity decrease grows as the air content rises. The velocity decline occurs more slowly at $x > 15$, and in the limit the velocity of the front tends to the sound velocity c_0 in the corresponding medium. The velocity of the front tends most rapidly to c_0 in water and in soil with $\alpha_1 = 0$, and this approach of D to c_0 occurs appreciably more slowly in soils containing air.

The dependence of particle velocity u on distance is shown in Fig. 3. The drop in the particle velocity for all the soils occurs most rapidly in the region close to the charge ($x \leq 15$), just as for the parameters p and D. In contrast to the parameters p and D, whose values are greater in the entire region of motion the lower the air content is in the medium, the particle velocity varies somewhat differently with distance, depending on the value of α_1. The greater the air content, the higher the particle velocity u is at $x \leq 2.5$, and already at $x \geq 4$ the nature of the dependence of u on α_1 is the opposite. The particle velocity in water is greater at all distances than in the remaining media.

The time dependences of the coordinate of the front are presented in Fig. 4. It follows from a comparison of the plots that the motion of the shock front depends to a significant extent on the air content in the soil; the larger α_1, the smaller the quantity R.

The variation of the particle velocity with time (particle coordinates x = 8.68, 31.72, and 59.98) is shown in Fig. 5a-c. It is evident that the lower the air content, the larger the particle velocity. At the same time, the rate of the velocity decline with time immediately after the arrival of the wave at a given point increases as the value of α_1 decreases. This situation points to the fact that higher-frequency waves propagate in denser soils, all other conditions being the same. After the interval of abrupt decay there comes an extended mildly sloping section of velocity decrease.

Experiments were conducted in water-saturated sand with the approximate component content $\alpha_1 = 0.1$, $\alpha_2 = 0.3$, and $\alpha_3 = 0.6$. Waves were produced in the soil by cylindrical explosive charges. The linear weight of the charge was determined by the number of detonating card fibers, and the number of fibers was varied from two to five in the experiments. Water saturation of the sand was carried out in a foundation pit 1.5 × 1.5 × 1.5 m in size whose bottom was treated with concrete, and the sidewalls were covered with polyethylene film. After each test the sand was removed from the foundation pit; then filling up of the foundation pit and water saturation were carried out again.

The pressures and waves created by the explosion were measured by high-frequency strain gauges whose signals were amplified by means of a UTS-1-12 strain station and recorded on an N-115 loop oscillograph. The gauges were mounted in the plane perpendicular to the charge axis at various distances from the axis.

The points in Fig. 6 correspond to the pressure values obtained experimentally. Curve 4 is obtained by solution of the problem and refers to soil approximately the same in component content as that in which the experiments were performed; the agreement of the calculated curve and the experimental points is completely satisfactory. The points in Fig. 4 reflect the dependence of the coordinate of the front of maximum pressures obtained by experimental means. The good agreement of the experimental and calculated data on the regularity of propagation of the wave front in the soil 4 (see Table 1) indicates that it is possible to consider the wave in the measured range of distances to be approximately a shock wave.

Thus, one can conclude as a result of comparison of the calculated and experimental data that the model [1] of multicomponent media permits a good description of the propagation of waves in water-saturated soils.

The author expresses his gratitude to G. M. Lyakhov and A. A. Vovka for posing the problem and discussing the research.

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