Determination of the Zone of Destruction of Soil and Rock Mass at Explosive Loads

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ABSTRACT

This paper studies the behavior of grounds and rock mass under explosive loads using a new worked out model of deformation of ground and rock mass accounting structural destruction of grounds. Here mechanical characteristics of grounds are the functions on the degree of structural destruction (on the second invariant of the deviator of deformation). The problem on excitation propagation from hemispherical cavity cut from ground half-space, to the sides of this cavity a load is applied, imitating the action of explosion. The problem is solved numerically - by the method of finite differences according to the scheme offered by Wilkins M.L. Solution of problem defines the dimensions of the craters and outburst ground as well as the zones of destruction of ground and rock mass.

INTRODUCTION

Cratering in nuclear and chemical explosions near the surface of ground media represents a physical and mechanical process; its study requires the application of various branches of science, such as the physics of radiation processes and chock waves, mechanics of ground and rock mass, hydro- and airo-dynamics; results of this study are important for different fields of human activity (in engineering, physics, geology, etc.). From the point of view of researchers in the field of the physics of radiation processes and explosions as well airo-dynamics of explosions the studies of cratering in ground and rock mass were carried out by many authors including Brode *et al* [1960], Yevterev [1973], Knowles *et al* [1977], Curran *et al* [1977], Larson [1982]. Theoretical and experimental methods of behavior of ground and rock mass under explosive loads were studied by Yevterev [1973], Oberbek [1971], Cooper *et al* [1977] and Vovk *et al* [1984]. In these papers theoretical design was carried out mainly for classic models of deformation (equations of state) of grounds using different conditions of yielding. In Knowles *et al* [1977] survey paper an analysis of criteria of ground destruction is given; these criteria being necessary for determinating relations. More improved Grigoryan's [1967] model of ground was used by Yevterev [1973] and Vovk *et al* [1984]. Physical parameters (that is energy and impulse transmitted to ground) depending on cratering define the motion and behavior of ground. The change of these parameters lead to the change of ground motion and respectively to the change of crater dimensions. Consider dynamic behavior of ground and rock mass under intensive short-term loads such as explosive ones. In the process of our consideration the main attention will be paid to the behavior of ground and rock mass in cases of application of different equations of ground state including the ones worked out by Khusanov *et al* [2000] and Sultanov *et al* [2000].

EQUATIONS OF STATE OF GROUND AND ROCK MASS

The behavior of the most of real grounds and rock mass differs from the one used in the problems of elastic or elastic-plastic idealization of deformation. In Bishop [1972], Rowe [1972], Vovk *et al* [1984] and Zamyshliayev *et al* [1990] it was stated that the deformation of ground and rock mass (with exception of structurally remolded soils and strongly loose sands) after reaching a certain point continues with decreasing stress till the moment when the stress becomes stable on a certain finite level. Accounting these characteristics of ground Bishop [1972] and Rowe [1972] offered the models of ground in which the yield limit of the ground after reaching the point of destruction becomes less down to its final level. Developing Grigoryan's [1967] models of deformation, Vovk *et al* [1984] and Zamyshliayev *et al* [1990] worked out different equations of state and models of dynamic destruction of grounds. Mainly these models of soil deformation show the dependence between the first invariants of stresses and strains. The regularity of shear deformation remains the same as in Grigoryan [1967]. On the basis of experimental studies Sultanov [1993] on underground structure - soil interaction under dynamic effect Sultanov [1998] offered non-linear models of ground at volume deformation. Here mechanical parameters of ground - a modulus of volume compressions is taken as some function depending on the degree of ground destruction. The models of ground with account of variability of mechanical parameters were offered also in Nelson *et al* [1971]. An attention should be paid to the fact that structural changes and destruction of soil according to results of experiments held by Bishop [1972], Rowe [1972], Vovk *et al* [1984] and Sultanov [1993] occur with formation of shear deformations. A complete structural destruction of soil or rock mass happens when the resistance of soil to shear forces is fully exhausted, that is at transfer to plastic flow of soil. Tests described in above mentioned papers reveal that even under insignificant loading the shear deformation of ground till its limit state has an irreversible character, and the values of shear modulus on obtained diagrams of intensities of tangent stresses versus shear deformation change together with the change of shear deformation (deviator of deformation). Hence taking shear modulus as a function on the second invariant of deviator of deformation the author with co-author Sultanov has worked out the equations of state of ground and rock mass in Sultanov *et al* [2000] and Khusanov *et al* [2000]. The equation of state of ground and rock mass at shear (Khusanov *et al* [2000]) accounting structural changes of ground, has the following form

$$\frac{d}{dt}\left(\frac{S_{ij}}{G(I_S)}\right)+\lambda\frac{S_{ij}}{G_*}=2\frac{de_{ij}}{dt} \qquad (1)$$

under loading ($de_{ij}/dt \geq 0$) and

$$dS_{ij}/dt = 2G_*\exp(\beta)de_{ij}/dt \qquad (2)$$

under unloading, that is at $de_{ij}/dt < 0$.

Here $G(I_S)=G_*\exp(\alpha(1-I_S)H(1-I_S))$; G_* - is the value of the modulus of shear of fully destructed soil, H - unit Heaviside function, $I_S=\sqrt{3}G_*\,\Gamma/Y(P)$ - parameters, characterizing the degree of structural change of ground, $\Gamma=\sqrt{2e_{ij}e_{ij}}$ - intensity of deviator of deformation, $Y(P)$ - function of plasticity of ground, α - initial value of empirical coefficient characterizing the degree of change of shear modulus, $\beta=\alpha^{(1-I_S')}$, I_S' - the value of the degree of destruction of ground at the moment of beginning of unloading. Parameter λ as in Grigoryan's [1967] model of ground deformation differs from zero only in past-limit deformation of ground. So its value in accordance to Khusanov *et al* [2000] is defined by relationship

$$\lambda=(2G_*W-dJ_2/dt)/(2J_2)$$

with fulfillment of yield condition

$$J_2=G_*\Gamma^2=Y(P)^2/3. \qquad (3)$$

Ways to determine the parameters of the models (1)-(3) are very simple and given in Sultanov *et al* [2000]. For complete determination of all parameters of equations (1)-(3) it is necessary to have experimental data for Grigoryan's [1967] classic equations of state of ground - the values of the modulus of volume compression and shear for undisturbed and fully destructed state of ground and rock mass, as well as strength parameters of soil to determine $Y(P)$. The values of parameter α (with exception of the initial one), β and I_S depend on prehistory of deformation as a function of deformation. The application of the model of shear deformation of ground (1)-(3) in numeric design is not difficult. To illustrate the diagrams of equations (1)-(3) in Khusanov *et al* [2000] by method of finite differences using Wilkins' [1964] scheme the problem was solved, its statement coincides with the test on pure shear held on the cut device.

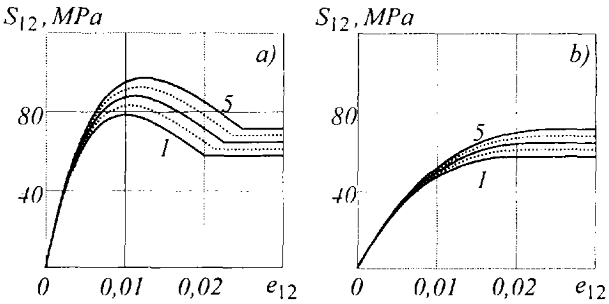

Fig.1. Diagrams of tangent stresses vs shear deformation.

Figure 1 shows the diagram of tangent stress versus shear deformation at different compacting values of pressure for undisturbed (*a*) and remolded soils with account of Coulomb'-Mohr's functions of yielding in condition (3). As it is seen from fig.1 in a diagram for undisturbed soils the peak value of tangent stress is observed and the influence of volume stress on tangent one is shown. The latter indirectly accounts for dilatational characteristics of ground. Run curves of tangent stress versus shear deformation quantitatively coincide with Garga [1970] experiments on shear with drainage of undisturbed and remolded specimens of soil in London. Diagram stress versus strain from (1)-(3) in the case of multiple loading - unloading is shown in fig.2 obtained by Khusanov *et al* [2000] in solving the same problem.

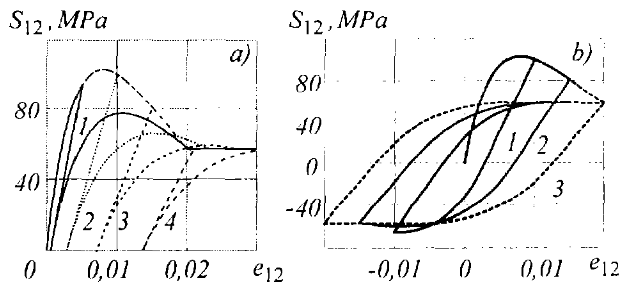

Fig.2. Change of tangent stresses versus shear deformation.

Hence it is seen that the equations of state (1)-(3) also take into consideration structural destruction of ground and rock mass at multiple loading without transfer to plastic flow. In conclusion it should be stated that the demonstration of equation of state of ground (1)-(3) - is an integral part of this work, because its parameters (α and I_S) in the process of deformation determine the state of destruction of ground and rock mass.

STATEMENT OF THE PROBLEM

At detonation of explosion device (mechanism) because of its natural dimensions a powerful shock wave is generated; it propagates both in ground and rock mass and above in the air. Wave dissipation in the air is accompanied with energy loss on ionization and radiation, and propagation in a rock mass - with loss on evaporation and fusion, plastic dissipation. As the density of the ground or rock mass is much greater than air density, we may consider that radiation energy is transferred and absorbed mainly in the air, and the effect on ground is connected with macro-motion of the charge steam (vapour) possessing high pressure and velocities. So explosion energy in a final stage is by some way redistributed between ground, air and charge steam. According to calculations given in Yevterev [1973] 1 micro-second after the initation approximately half of the explosion energy is radiated in the air, and the other half is presented in the form of kinetic and potential energy of charge steam. So, to describe the effect of explosion on ground we may assume the following scheme from lower ground half-space a hemisphere with radius r_0 is cut, in which the part of energy remained from radiation to air and taken as initial one is propagated. Then, according to propagation of initial energy there are different approaches: 1) initial energy is propagated in hemisphere with radius r' - here r' is a natural radius of the charge. Here according to Yevterev [1973] the equation of state of charge steam is taken as coinciding with the equation of state of the ground; 2) initial energy is propagated in hemisphere of the radius r'', where r'' - is a border of the zone of evaporation, this approach is used in Brode *et al* [1960] and Yevterev [1973]. According to these papers at dilatation of explosion products a powerful shock wave is generated, it evaporates ground and rock mass. With its propagation the larger massives of rock mass are evaporated forming a quickly growing cavities. After reaching on the front a certain critical density of the energy depending on physical and chemical characteristics of the rock the evaporation stops. Naturally to study the mechanical behavior of ground and rock mass and the zones of their structural destruction it is advisable to take the radius of the hemisphere as an initial one and to carry out design. In Cooper *et al* [1977] it is supposed that qualitative peculiarities of the phenomena connected with late stage of cratering and its characteristic motion of ground may not depend on the details of the source of explosion. These considerations were approved in Maxwell *et al* [1975]. So consider the motion of ground half-space under the effect of normal loads (pressures), changing in time on the border of cut hemisphere. The equations of continuity and motion of the ground have the form

$$\frac{d\rho}{dt}+\left(\frac{\partial U_x}{\partial x}+\frac{\partial U_z}{\partial z}+\frac{U_x}{x}\right)=0, \tag{4}$$

$$\rho\frac{dU_x}{dt}=\frac{\partial\sigma_{xx}}{\partial x}+\frac{\partial S_{xz}}{\partial z}+\frac{\sigma_{xx}-\sigma_{\theta\theta}}{x},\qquad \rho\frac{dU_z}{dt}=\frac{\partial\sigma_{zz}}{\partial z}+\frac{\partial S_{zx}}{\partial x}+\frac{S_{xz}}{x}; \tag{5}$$

Here U_x, U_z - mass velocity components of corresponding directions of cylinder system of coordinates. Total stresses $\sigma_{xx}, \sigma_{zz}, \sigma_{\theta\theta}$ are defined from the relationships

$$\sigma_{xx}=S_{xx}-P,\quad \sigma_{zz}=S_{zz}-P,\quad \sigma_{\theta\theta}=S_{\theta\theta}-P, \tag{6}$$

The system of equations (4)-(6) with equations of state (1)-(3) at shear and with Grigiryan's [1967] equations at volume deformation

$$P(\rho)=\frac{K}{n}\left(\left(\frac{\rho}{\rho_0}\right)^n-1\right), \tag{7}$$

as well with relationships determining the connection between the deformation and particle velocity

$$e_{xx}=\frac{\partial U_x}{\partial x},\quad e_{zz}=\frac{\partial U_z}{\partial z},\quad e_{\theta\theta}=\frac{U_x}{x},\quad e_{xz}=\frac{1}{2}\left(\frac{\partial U_z}{\partial x}+\frac{\partial U_x}{\partial z}\right) \tag{8}$$

with initial and boundary conditions describes the dynamic behavior of soils. As in equation (4) there is no mass force (gravity force), an initial conditions may be taken as equal to zero (the ground is considered at rest and unstressed). As a boundary conditions on the surface of ground half-space (at z=0) according to Yevterev [1973] the condition of free surface is taken and on the sides of cut hemisphere ($x=r_0$) the pressure with signal $P_0(t)=at+b$ at $0\le t\le t_1$, $P_0(t)=$ $=B\exp(-\gamma t)$ at $t>t_1$ is applied. The choice of such form of a signal is caused by the fact that two-wave structure of the field of stresses in grounds beyond the zones of plastic flow according to Yevterev [1973] takes an above-mentioned form.

ON THE METHOD OF SOLUTION OF THE PROBLEM

The system of equations (1)-(8) is solved numerically by the method of finite differences.

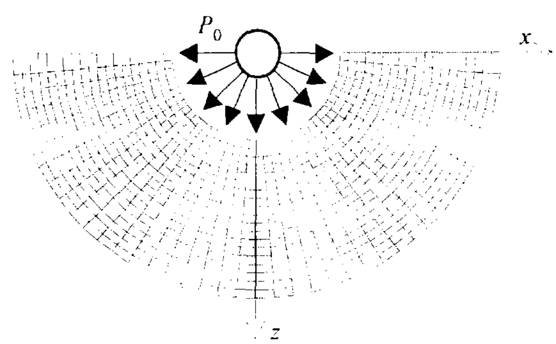

Fig.3. Design grid at initial moment of time.

Together with boundary conditions they are approximated on the grid of quadrangular cells; their initial configuration is shown on fir.3. Approximation of equations (1)-(8) is carried out in accordance with two-dimensional finite-differential scheme "HEMP" offered by Wilkins' [1964]. To evaluate the reliability and correctness of numeric calculations the test examples were solved and their results were compared with results of exact analytical solutions of the problems on propagation of elastic excitations initiated from the cavities of the radius (Vovk *et al* [1984]) and with results numeric solutions given by Brode *et al* [1960]. It should be stated that in order to obtain a good coincidence of these results a different artificial viscosity's were added and the procedures of smoothing the parameters offered by Yevterev [1973] were carried out.

NUMERIC CALCULATIONS AND THEIR ANALYSIS

Consider results of calculation. A geometric picture of ground motion shown in fig.4 is of great interest; design field (r_0 =2 m) at the moment of time t=2 and 10 ms using an equations of state (1)-(3), (4) and at the moment of time t=2 ms in case of elastic-plastic deformation of ground according to Grigoryan's [1967] model (fig.4,*c*). Physical and mechanical characteristics of ground were taken as follows: an initial density ρ_0=2670 kg/m^3, Poisson's ratio ν=0,25, modulus of shear of completely destructed ground G_*=14,4 GPa, yield limit Y=const=0,1 GPa, parameter α_0=2.

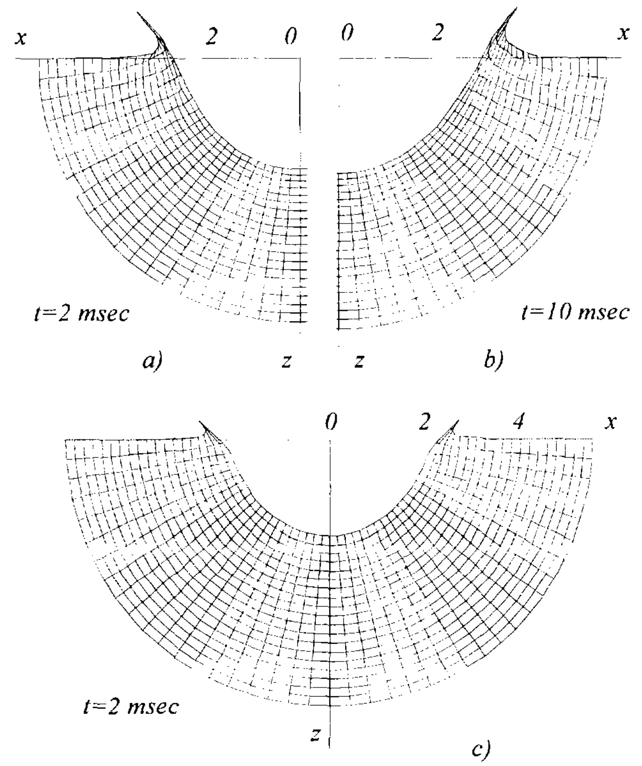

Fig.4. Design grid field to the moments of time t=2 ms (a) and t=10 ms (b) using equations of state (1)-(3) and t=2 ms using Grigoryan's model.

Parameters of acting explosive load were taken in such a way that maximum pressure at the moment of time t_1=1 mcs should reach the value of 4,2 GPa and the degree of damping was taken as equal to $1/\gamma$=0,3 ms. Further variants were considered when $1/\gamma$=0,1 ms, 0,3 ms and 0,5 ms (curves 1-3 respectively, fig.5) obtained change of pressure on the sides of the hemisphere versus time is shown in fig.5.

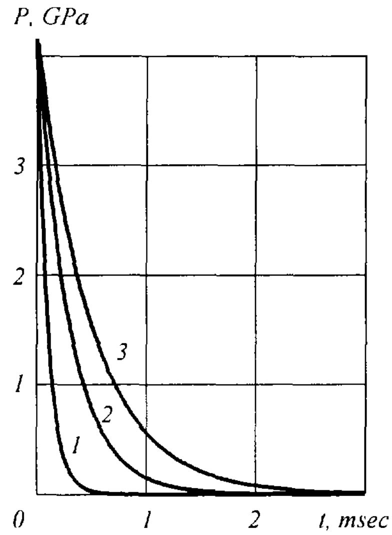

Fig.5. Change of acting pressure on the sides of cut hemisphere in time.

Under loads of the type shown in fig.5 maximum stresses are obtained near the side of the hemisphere of ground half-space. Change of longitudinal stress in time in the case when $1/\gamma$=0,3 ms in fixed points in section x=0 is given in fig.6.

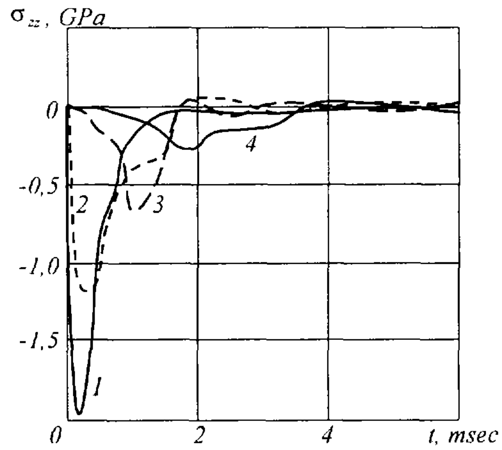

Fig.6. Change of stresses in time in fixed points of ground. 1 - z=2,1 m; 2 - z=2,9 m; 3 - z=4,9 m; 4 - z=7,9 m.

As it is seen from fig.6, the longer is the distance from the point of load application the less is an amplitude of maximum stresses. Figure 7 shows that the increase of time of load action leads to increase of crater dimensions. Here an initial dimension of ground crater after stoppage of ground evaporation from the explosion does not significantly influence on a further outburst of the ground. With time the behavior (stress-strain state) of ground or rock mass is stabilized (fig.6).

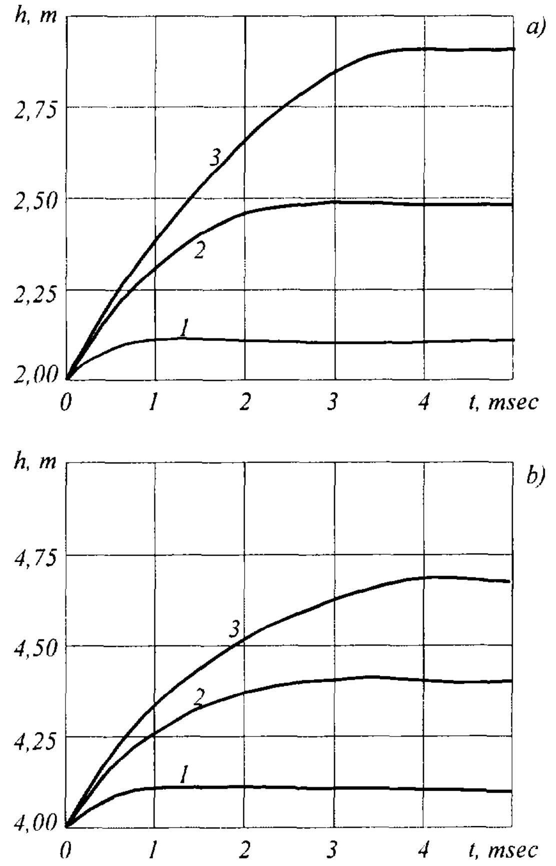

Fig.7. Change of the depth of the crater in time at r_0 =2 m (a) and r_0 =4 m (b). 1- $1/\gamma$=0,1ms; 2- $1/\gamma$=0,3 ms; 3- $1/\gamma$= 0,5 ms.

For a discussed explosion load the motion of ground as well as the process of cratering ends at initial moments of time (according to fig.7 at $1/\gamma$=0,5 ms the stabilization of cratering occurs till t=4 ms). According to the behavior of parameter I_S in equation of state (1)-(3) of ground or rock mass we may determine the degree of destruction of ground or rock mass in arbitrary region. Change of this parameter in depth in section x=0 at the moment t=10 ms after the action of explosion load is given in fig.8.

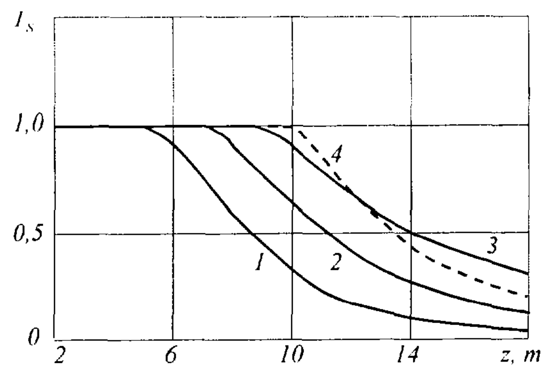

Fig.8. The degree of destruction of ground in depth.

In those points where the degree of destruction equals to one the particles of ground medium are taken as completely damaged or remolded. In this region the ground stresses transfer from their peak value (fig.1,2) and strength characteristics of ground or rock mass take less values that also does not qualitatively contradict the results of experiments on contact explosions. As it is seen from fig.8, to obtain vast zones of destruction (crushing) of ground or rock mass (which is important in mineral production by open-cut mining) it is necessary to increase the duration of load action. The increase of duration after the evaporation of explosion effect may be reached by different ways. First of all it depends on physical and chemical composition of exploding substance, its power and characteristics of ground surrounding evaporation zone; all this represents a separate problem for further studies. In analogy with fig.8 according to the character of obtained values of the parameter I_S we may determine the boundaries of the zone of destruction of ground (fig. 9-10).

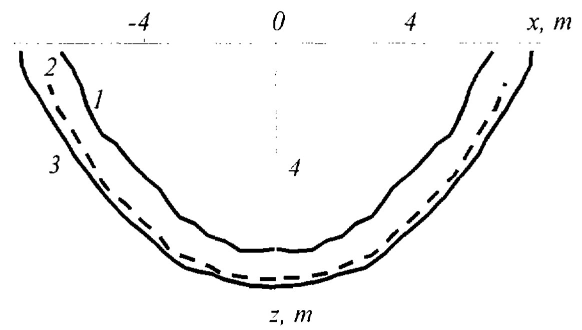

Fig. 9. Boundaries of the zone of destruction of ground at r_0=2m. 1 - t=1 ms; 2 - t=1,5 ms; 3 - t=5 ms.

Figure 9 shows that at r_0=2 m and $1/\gamma$=0,3 ms destructed zone of ground is formed during 2 ms after explosion evaporation (curves 2 and 3). Then with time the boundary of destructed zone remains invariable.

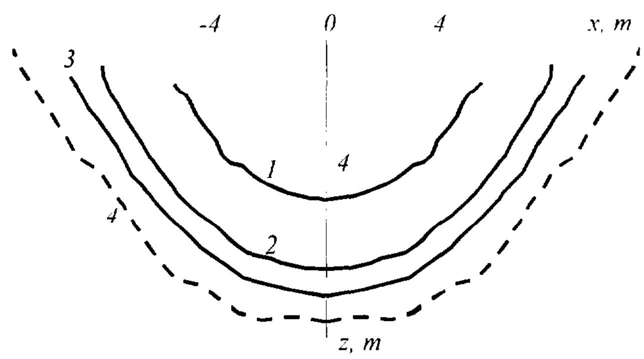

Fig. 10. Destructed zone of ground at r_0=2 m (solid lines) and r_0=4 m (dotted lines). 1- $1/\gamma$=0,1ms; 2- $1/\gamma$=0,3 ms; 3- $1/\gamma$= 0,5 ms; 4- $1/\gamma$=0,3 ms.

The boundaries of the zones of destruction given in fig.10 correspond to the moment of time t=5 ms.

CONCLUSION

So an obtained pattern of cratering and zones of destructions of ground qualitatively coincides with test studies (basic conclusions are given in the analysis of results presented). For quantitative analysis it is necessary to carry out a design with account of initial stages of the explosion, the motion of fume part with transition of real energy of the explosion to ground; and also to account gravitational forces and initial tectonic stress state of the rock. On the whole, using the equation of state of the ground (1)-(3) and with account of above-mentioned factors we may succeed in obtaining a sought for results in theoretical design to use them in practice.

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