We prove the first equality, while the proof for the second is analogous. We have

$$\lim_{n\to\infty}\int_\Omega (u_* - u^n)^2\,d\Omega = \lim_{n\to\infty}\left(\int_\Omega u_*^2 d\Omega - \frac{2}{(1+n)}\sum_{i=0}^{n}\int_\Omega u_* u_i^n d\Omega + \frac{1}{(1+n)^2}\sum_{i,j=0}^{n}\int_\Omega u_i^n u_j^n d\Omega\right). \tag{2.1}$$

We use the form of the functions u_i^n and u_* and also standard formulas from the theory of series to get after integration that

$$\begin{gathered}\int_\Omega u_*^2 d\Omega = \frac{5+\pi}{12},\quad \frac{1}{(1+n)}\sum_{i=0}^{n}\int_\Omega u_* u_i^n d\Omega = \frac{5+\pi}{12} - \frac{1}{48n},\\ \frac{1}{(1+n)^2}\sum_{i,j=0}^{n}\int_\Omega u_i^n u_j^n d\Omega = \frac{5+\pi}{12} - \frac{4+\pi-2n}{48n(1+n)}.\end{gathered} \tag{2.2}$$

We substitute (2.2) into (2.1) to get

$$\int_\Omega (u_* - u^n)^2\,d\Omega = \frac{6+\pi}{48n(1+n)},$$

where the right side tends to zero for n → ∞. It has thereby been shown that the continuous solution for the velocities of (1.1) is the limit to the sequence of discontinuous solutions.

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CHANGE IN THE FILTRATION PARAMETERS OF A SATURATED COLLECTOR DUE TO A CONFINED EXPLOSION

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1. It has now been quite definitely established that the permeability of a monolithic rock of granite type increases by up to 4-5 orders of magnitude after a contained explosion by comparison with the initial permeability, which is extremely small (0.01 mD). The permeability of coal after an explosion increases more moderately (by 2 orders), while the initial permeability is of the order of 100 mD [1, 3]. In both cases there is a monotone fall in the permeability to the peripheral initial value away from the explosion cavity. In these media the improvement in the permeability is due to the explosive generation of radial and other crack systems.

On the other hand, a contained explosion in an air-dry porous highly permeable medium leads [4] to a substantial fall in the permeability everywhere around the explosion cavity, in spite of the dilatation. There is marked improvement in the hydraulic permeability due only to passage of individual joints near the explosion cavity. Therefore, the irreversible changes in permeability produced in porous rocks by explosion are due to competing mechanisms of fracturing and pore consolidation. The parameters of the irreversible rock deformation corresponding to appreciable permeability change are the damage [3] (i.e., the jointing) and the extremely small residual strain (0.01%).

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If the pore space contains a liquid, the character of the rock deformation is altered. If there is irreversible dilatation, there is a fall in the pore pressure, and as a result the shear strength expressed in terms of effective Tertsagi stresses [5] will increase, while consolidation increases the pore pressure and reduces the strength. Therefore, pore filling smooths out the differences and changes the character of the damage. In weak (soft) saturated soils and rocks, the explosion waves are closely described by the hydrodynamic approximation [5, 6], the main damage is of displacement type, and there are pulsations in the explosion cavity when the explosion is contained, as in an underwater explosion [7]. Also, the explosion raises the pore pressure in substantial regions [8, 9], and this persists for a long time.

On the other hand, the hydraulic permeability of a porous medium is very sensitive to small irreversible strains (microscopic damage). Therefore, an explosion in a saturated rock may lead to different and nonmonotonic changes in the filtration parameters, including slight changes at considerable distances, the exact effect being dependent on the microscopic damage.

2. To examine the effects of an explosion on a typical productive collector we chose a highly porous permeable cemented medium to simulate an explosion. The deformation characteristics of cemented and crystalline rocks differ substantially [10]. Most oil deposits contain highly variable cemented collectors [11, 12], but our model for a medium was similar to a terrigenous collector. The model was made from treated KP-3 sand, lime flour, and water glass, which was the cementing material. The model was placed in a metal vessel of height 350 mm and diameter 300 mm. The dimensions of the model and the maximum discharge size were chosen on the basis that the time of cavity development was less than twice the time required for the compression wave to reach the boundary of the model [13] and such that the boundary separating the zones of residual and elastic strains did not lie outside the model.

The mixture of KP-3 sand, lime flour, and water glass was kept in a dessicator at 100-120°C for 50-55 h. This gave a collector with the following physicomechanical properties: density $\rho = 1.85 \cdot 10^3$ kg/m^3 (in the unsaturated state), porosity m = 25%, gas permeability k = 150 mD, strength in uniaxial compression $\sigma^* = 25$ MPa, push-wave speed in the saturated state $c_l = 3150$ m/sec, and Poisson ratio $\nu = 0.22$.

To place the charge in the model we produced a model for a borehole of depth up to 160 mm and diameter 12 mm, which after emplacement of the charge was filled with epoxide resin. We used ten charges of diameter 10 mm and mass 0.76 g (trotyl equivalent 1.06 g).

The experiments were performed with models in which the pores had been filled to almost 100% with kerosene. We examined the mechanical effects of the explosion on the kerosene-saturated collector and the associated changes in the filtration parameters from the explosion cavity to the periphery.

The following methods were used to examine the mechanical effects: visual examination of the deformation from the center to the periphery (cavity, cracks, general state of a medium), change in density from the cavity to the periphery, and change in elastic-wave speed from the cavity to the periphery as measured with ultrasound.

The method of visual examination was as follows. Before the explosion the model in its metal shell was equipped with plates at the ends to eliminate the occurrence of cracks around the perimeter in the plane of the charge arising from the negative-pressure wave, which may substantially influence the filtration parameters after the explosion. The medium in the model was under a background pressure of about 0.3 MPa. After the explosion the model was released from the metallic shell and was cut in cross section in the plane of the charge. We determined the size of the cavity, the number and length of the cracks, the general state of the medium around the cavity (connectedness and deformation), and the state of the tubes for measuring the filtration parameters.

A universal gamma-gamma density gauge type UGGP-1 was used to determine the density changes by zones outwards from the center. This was a densitometric method of recording the scattered gamma radiation using a narrow gamma-ray beam. This gamma-gamma method involves recording the gamma rays scattered in the material (the method and the measurements were operated in collaboration with G. I. Khovrin and L. B. Prozorov).

The changes in elastic-wave speed were measured with a UKB-1M apparatus, using special small transducers with natural resonant frequencies of 150 and 800 kHz. The properties of the medium were determined by passing the ultrasound through the model along the radius from the center with points of measurement at intervals of 0.5-2.0 cm. To determine the the changes in properties after the explosion, a disk was cut from the model in the plane of the charge of thickness about 5 cm, where transmission measurements over the

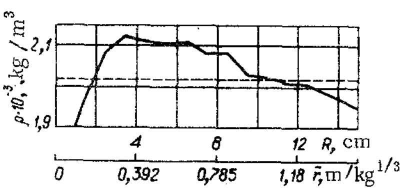

Fig. 1

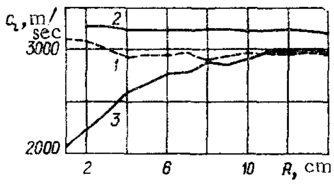

Fig. 2

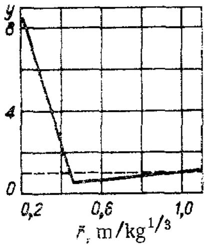

Fig. 3

TABLE 1

Zone	R, mm	R/R_e	$\bar{r}$
R_c	11,0	2,2	0,11
R_d	90,0	18	0,88

thickness and profiling with a step of 0.5 cm gave the longitudinal-wave speeds (methods and measurements operated in collaboration with Yu. F. Trofimov and N. I. Seleznev). These same disks were used with the same profiles to determine the density.

To examine the changes in filtration parameters, tubes of diameter 3 mm were fitted into the model during preparation, whose ends were perforated over a length of 15-20 mm. The opposite ends of the tubes emerged from the model and were joined to a UIPK apparatus. The tubes lay in the horizontal plane of the charge or else below the charge at distances of 2 to 14 cm, with 8 or 9 tubes in one experiment. The model was enclosed in a steel cylinder, which was sealed at the ends by flanges; the sealing at the points of junction was provided by rubber inserts in slots, while the point of emergence of the tube from the model was sealed with epoxide resin. We determined the kerosene flow rate with a steady pressure difference between a pair of tubes before and after the explosion. The ratio $Q/\Delta p$ was used as the filtration characteristic between a pair of tubes, where Q is the kerosene flow rate and Δp is the steady pressure difference between the tubes, i.e., we determined the permeability over a given area. The change in the filtration parameters as a result of the explosion was estimated as $Q/\Delta p/(Q/\Delta p)_0$, where the subscript 0 relates to the state before explosion.

3. Visual examination revealed a nearly spherical cavity around the charge. Cracks and other damage were not observed around the cavity. Within a radius of $\bar{r} \simeq 0.8$-1.0 m/kg$^{1/3}$, the matrix after the explosion was less consolidated ($\bar{r} = R/W^{1/3}$ is the radius referred to the charge size). The deformation zones are shown in Table 1, where R_c is the cavity radius, R_d is the radius of damage to the connectedness, and R_e is the radius of the explosive.

The density distribution after the explosion is such that two zones can be distinguished around the cavity (Fig. 1): loosening and consolidating ones. The first shows a maximum decrease in density near the cavity of 10%, and this extends out to a radius $\bar{r} \simeq 0.22$ m/kg$^{1/3}$, while the consolidation zone is present in the range of reduced distances from $\bar{r} \simeq 0.22$ to $\bar{r} \simeq 0.8$-1.0 m/kg$^{1/3}$. The maximum consolidation in this region is 5%. There was a certain reduction in the density at the periphery of the model, which is related to the preparation conditions, since the stress at the center is higher than at the periphery during pressing of the raw material. The measurement results on the disk cut after the explosion are shown in Fig. 2, which shows that the wave speed is minimal at the cavity (about 60% of the initial value) and rises to the initial value at $\bar{r} \simeq 0.9$-1.0 m/kg$^{1/3}$ (curve 1 before saturation with kerosene, 2 after saturation, and 3 after explosion).

Therefore, a contained explosion in a highly porous saturated collector does not produce visible cracks, but it alters the pore space, and this should be examined by means of polished sections or other microscopic methods. The explosion produces two successive zones: consolidation and deconsolidation.

4. Figure 3 shows the results on the filtration performance after the explosion. There is a sequence of three zones outwards from the cavity. The first is characterized by a substantial improvement in the filtration parameters (by an order of magnitude near the cavity), the radius being $\bar{r} \simeq 0.45$ m/kg$^{1/3}$. In the second zone, the explosion adversely affects the properties, which on average are reduced by 30-40% from the initial values, and this region is present in the distance range from $\bar{r} \simeq 0.45$ to $\bar{r} \simeq 0.1$ m/kg$^{1/3}$. Outside distances of $\bar{r} \simeq 1.0$ m/kg$^{1/3}$ there is a zone of slight improvement in the filtration parameters. The dimensions of this third zone and the changes in the filtration in it were not especially examined in these experiments.

Least-squares fitting gave the following relationships for the parameters against the reduced distance. In the first zone $y = -31.7\bar{r} + 15$, $0.22 \leq \bar{r} \leq 0.45$, in the second $y = 0.96\bar{r} - 0.01$, $0.45 \leq \bar{r} \leq 1$, where $y = (Q/\Delta p)/(Q/\Delta p)_0$.

Therefore, the change in filtration parameters in a contained explosion is nonmonotonic, and the effects are radically different from those on the hydraulic permeability of monolithic rocks and air-dried porous media.

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