Journal of Applied Mechanics and Technical Physics, Vol. 47, No. 1, pp. 109–115, 2006

EXPERIMENTAL STUDY OF THE PRODUCTIVE BED FILTRATION MODE CHANGED BY AN UNSTEADY ACTION ON THE HOST ROCK BLOCKS

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UDC 539.3

A laboratory study including physical modeling of filtration processes in porous beds with similarity criteria satisfied is performed. It is demonstrated that weak dynamic actions on stressed host rock blocks can initiate repacking of the system of blocks, leading to an increase in pressure in the productive bed and in oil recovery.

Key words: *increase in oil recovery, filtration, unsteady action, laboratory experiment, similarity criteria.*

Introduction. Methods of intensification of oil production and increasing the hydrocarbon recovery ratio are normally based on processes that occur in the productive bed (intrabed combustion, effect of electric fields, displacement, addition of surfactants, mechanical cleansing of the bottom-hole area, hydraulic fracturing, geological ripping, etc.) [1–6]. It was demonstrated theoretically [7] that low-frequency vibrations can generate high-frequency fields in heterogeneous multiphase media, which can be the reason for more intense oil recovery from oil beds. In modeling the unsteady treatment of the block reservoir, it was assumed [8] that actions with an amplitude of the order of several angstroms can result in rotation of blocks, corresponding changes in permeability of the medium and the fluid-flow structure, and, as a consequence, greater production rate. It should be noted that the host medium (rock massif) has a block structure as well [9]. Under an unsteady action from the surface, displacements in the overburden are greater than those in the oil bed. Therefore, external loads can induce irreversible processes in the host medium: microdisplacements of blocks, which can lead, under certain conditions, to changes in the production rate of productive wells [10, 11]. The duration of vibrations necessary for implementation of such a mechanism in a structured rock massif is estimated in [12].

Based on the theoretical model developed in [11], the present work deals with experimental justification of the mechanism of increasing oil recovery, involving deliberate changes in oil-bed pressure caused by redistribution of stresses in the host block massif, which, in turn, is induced by an external unsteady action.

1. Parameters of the Test Bench. The prototype of the laboratory model (Fig. 1) was part of a typical vertical cross section (passing through a productive well) in the vicinity of one of the oil-bearing beds of the Pravdinskoe oil field. Table 1 lists the basic parameters and their numerical values (columns 1 and 3, respectively): time t, distance to the recharge well (or length of the external boundary) L, bed thickness h, porosity m, $\Delta p = p_c - p_0$ (p_c and p_0 are the initial pressure in the oil bed and atmospheric pressure), viscosity and density of the fluid μ and ρ_f,

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Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 47, No. 1, pp. 131–138, January–February, 2006. Original article submitted October 25, 2004; revision submitted March 14, 2005.

TABLE 1

Notation	Measurement unit	Real values	Relations between real and model parameters	Model values	Criterion satisfied (+) or failed (−)
1	2	3	4	5	6
Oil bed and fluid					
t	sec	—	$t^{\rm m} = \sqrt{\delta}\, t^{\rm r}$	—	+
h	m	10–50	$h^{\rm m} = \delta h^{\rm r}$	0.05	+
L	m	400–500	$L^{\rm m} = \delta L^{\rm r}$	0.4	+
m	%	20	$m^{\rm m} = m^{\rm r}$	20	+
Δp	MPa	20–30	$\Delta p^{\rm m} = \delta \Delta p^{\rm r}$	0.03	+
μ	Pa · sec	0.85–0.90	$\mu^{\rm m} = \delta^{3/2} \mu^{\rm r}$	0.001	−
ρ_f	kg/m^3	850	$\rho_f^{\rm m} = \rho_f^{\rm r}$	1000	+
$\dot{Q}$	m^3/sec	$7 \cdot 10^{-4}$	$\dot{Q}^{\rm m} = \delta^{5/2} \dot{Q}^{\rm r}$	10^{-11}	+
χ	m^2/(Pa · sec)	$7 \cdot 10^{-12}$	$\chi^{\rm m} = \sqrt{\delta}\, \chi^{\rm r}$	$3 \cdot 10^{-13}$	+
Host medium					
σ_V	MPa	40	$\sigma_V^{\rm m} = \delta \sigma_V^{\rm r}$	0–0.05	+
E	GPa	25–40	$E^{\rm m} = \delta E^{\rm r}$	12	−
ρ	kg/m^3	2000	$\rho^{\rm m} = \rho^{\rm r}$	1800	+
ε	%	0.10–0.16	$\varepsilon^{\rm m} = \varepsilon^{\rm r}$	10^{-4}	−
w	m	10^{-5}	$w^{\rm m} = \delta w^{\rm r}$	$\geqslant 2 \cdot 10^{-8}$	+
d	m	50–500	$d^{\rm m} = \delta d^{\rm r}$	0.05	+
f	Hz	1–20	$f^{\rm m} = f^{\rm r}/\sqrt{\delta}$	30–600	+
Joints					
φ	deg	5–35	$\varphi^{\rm m} = \varphi^{r}$	7.3	+
C	MPa	0–0.5	$C^{\rm m} = \delta C^{\rm r}$	$2 \cdot 10^{-5}$	+

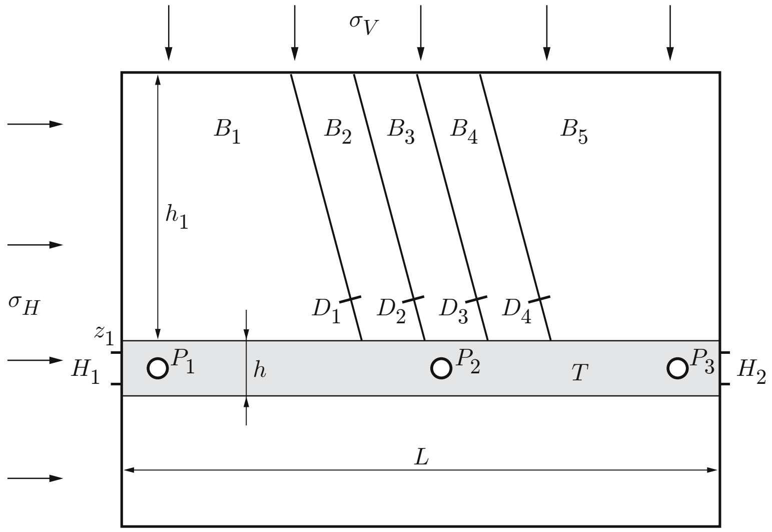

Fig. 1

μ and ρ_f, permeability K, $\chi = K/\mu$, production rate of the well Q, Young's modulus and density of the host rocks E and ρ, lithostatic stress at the upper boundary of the object considered $\sigma_V = \rho g (z_1 - h_1)$, production depth z_1, acceleration of gravity g, strain ε, thickness of blocks d, angle of internal friction φ, adhesion of interblock joints C, amplitude of the displacement generated in the vicinity of the oil field by the external action w, and frequency of the external action f.

The following criteria of similarity were used to determine the parameters of the laboratory model and the test-bench structure [13, 14]:

geometric criterion

$$L^{\mathrm{m}}/L^{\mathrm{r}} = a_{\mathrm{g}}, \tag{1}$$

kinematic criterion

$$t^{\mathrm{m}}/t^{\mathrm{r}} = a_{\mathrm{k}}, \tag{2}$$

and dynamic criterion

$$\rho^{\mathrm{m}}/\rho^{\mathrm{r}} = a_{\mathrm{d}}. \tag{3}$$

Based on these criteria, it is possible to derive relations between all model (superscript "m") and real (superscript "r") parameters, for instance:

$$E^{\mathrm{m}} = \frac{E^{\mathrm{r}} a_{\mathrm{d}} a_{\mathrm{g}}^2}{a_{\mathrm{k}}^2}, \quad f^{\mathrm{m}} = \frac{f^{\mathrm{r}}}{a_{\mathrm{k}}}, \quad g^{\mathrm{m}} = \frac{g^{\mathrm{r}} a_{\mathrm{g}}}{a_{\mathrm{k}}^2}, \quad \mu^{\mathrm{m}} = \frac{\mu^{\mathrm{r}} a_{\mathrm{d}} a_{\mathrm{g}}^2}{a_{\mathrm{k}}}, \quad \varepsilon^{\mathrm{m}} = \varepsilon^{\mathrm{r}}, \quad K^{\mathrm{m}} = K^{\mathrm{r}} a_{\mathrm{g}}^2. \tag{4}$$

The numerical values of the similarity coefficients a_{g}, a_{k}, and a_{d} were chosen from the following considerations. The weight of the blocks B_i (see Fig. 1) should be comparatively small, and the displacement probes D_j should be able to register the value of $a_{\mathrm{g}} w^{\mathrm{r}}$. As a favorable effect of vibrations on the oil bed was reached in real conditions with $w \approx 10^{-5}$ m [15], and the sensitivity threshold of D_j was approximately 10^{-8} m, we assumed that $a_{\mathrm{g}} = \delta = 0.001$.

Under laboratory conditions, it is impossible to simultaneously satisfy the similarity criteria in terms of stresses and strains. Available artificial materials with a very low Young's modulus do not allow a direct unsteady action on the block model. Therefore, a reconciling situation was chosen: the first condition in (4) was abandoned, and the blocks were made of concrete ($E^{\mathrm{m}} = 12$ GPa), which yielded $a_{\mathrm{d}} = 1$. This compromise did not affect the quantitative results because irreversible deformations in a structured rock massif were localized in fault regions [9], and the properties of interblock joints of the model agreed with the real properties (see Sec. 2).

The obvious condition $g^{\mathrm{m}} = g^{\mathrm{r}}$ and the third relation in (4) yield $a_{\mathrm{g}}/a_{\mathrm{k}}^2 = 1$; hence, $a_{\mathrm{k}} = \sqrt{\delta}$.

Column 4 of Table 1 gives the final relations between the real and model parameters, which were obtained with the use of criteria (1)–(3); the numerical values of the model parameters are listed in column 5; the plus or minus sign in column 6 indicates whether the criterion of similarity in terms of this parameter is satisfied.

2. Estimate of Properties of Interblock Joints. In experimental determination of strain and strength in disturbances (tilt test), the properties of the contacting surfaces are changed, especially at high stresses. Therefore, polished glass was glued onto one side of the blocks B_i ($i = 1, \ldots, 4$) to ensure repetition of tests. Quantitative estimates of φ and C were obtained in a separate auxiliary experiment (Fig. 2). A rotating platform was loaded by two neighboring blocks B_i and B_{i+1} (the lower block was motionless; W_i^1 is the weight of the block B_i and S is the joint-surface area), and the tilt angle of the platform was smoothly increased from $\beta = 0$ to $\beta = \beta_i^1$ corresponding to the moment the block B_i started to slip down. A similar procedure was performed for the weight of the block B_i increased to W_i^2 with the angle β_i^2 being fixed.

We assume that the ultimate shear stress τ_i in the joint between B_i and B_{i+1} is related to the normal shear stress σ_i by the Mohr–Coulomb law: $\tau_i = \sigma_i \tan \varphi_i + C_i$ [16]. Then, we obtain the obvious relations (see Fig. 2)

$$\tau_i^l = W_i^l \sin \beta_i^l / S, \quad \sigma_i^l = W_i^l \cos \beta_i^l / S, \quad \tau_i^l = \sigma_i^l \tan \varphi_i + C_i$$

($l = 1, 2$), which yield

$$\varphi_i = \arctan \Big(\frac{\sin \beta_i^1 - p \sin \beta_i^2}{\cos \beta_i^1 - p \cos \beta_i^2} \Big), \qquad C_i = \frac{W_i^2}{S} \, \frac{\sin (\beta_i^1 - \beta_i^2)}{\cos \beta_i^1 - p \cos \beta_i^2},$$

where $p = W_i^2 / W_i^1$.

The mean values of φ^{m} and C^{m} listed in column 5 of Table 1 for all pairs of blocks $\{B_i, B_{i+1}\}_{i=1,2,3}$ show that the relations between the model and real values of the angle of internal friction and adhesion, which are required by the similarity criteria used, are ensured.

3. Filtration Characteristics of the Oil Bed. The prototype was a productive well with a comparatively low daily production rate ($Q^{\mathrm{r}} = 60$ m^3); hence, the mean flow rate was $\dot{Q}^{\mathrm{r}} = 0.0007$ m^3/sec.

We determine the mass M_s of dry sand of density $\rho_s = 1750$ kg/m^3, which should be used to fill the tank T (see Fig. 1) to model the filtration process with a satisfied condition $m^{\mathrm{m}} = m^{\mathrm{r}}$: $M_s = (1 - m^{\mathrm{r}}) \rho_s V = 4.12$ kg, where $V = 0.003$ m^3 is the volume of T.

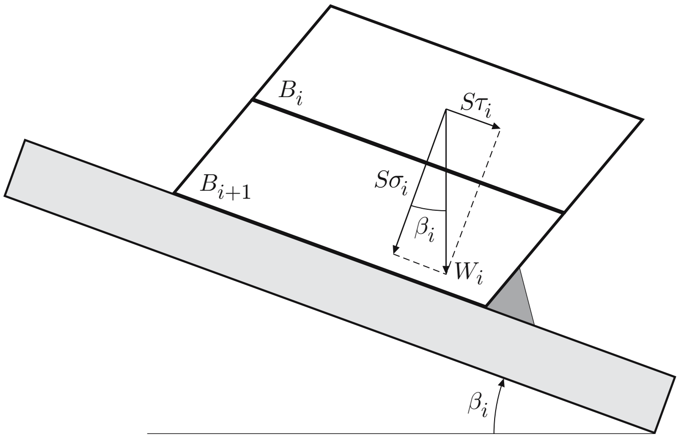

Fig. 2

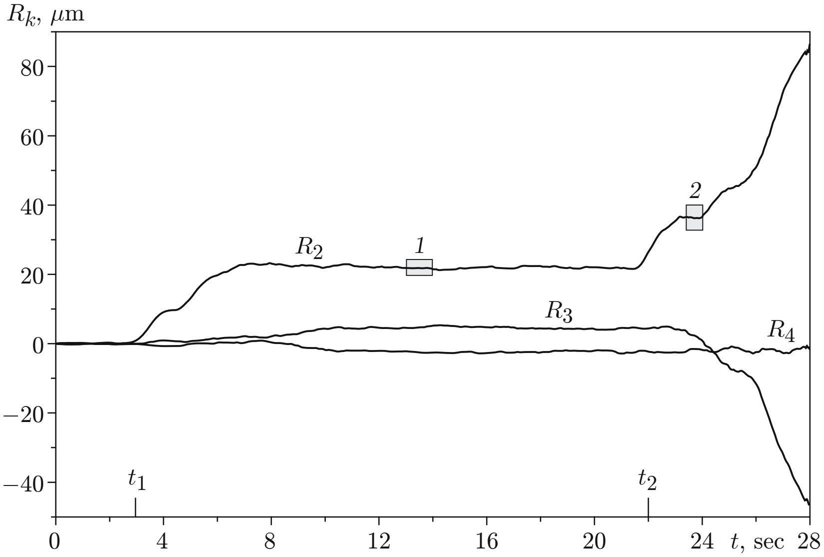

Fig. 3

The dynamic viscosity of the filler (water) is two orders of magnitude lower than that of oil, and the criterion in terms of μ is not satisfied (see Table 1). It is of interest, however, to consider the integral characteristic of the process: flow rate, which depends on the parameter χ. The numerical value of χ^{m} was evaluated empirically: the constant flow rate $\dot{Q}_0$ was measured in the steady filtration mode with a prescribed pressure difference Δp^{m}; then the Darcy law predicts $\chi^{\mathrm{m}} = \dot{Q}_0 L^{\mathrm{m}}/(s\Delta p^{\mathrm{m}})$, where s is the cross-sectional area of the output hole H_2 (see Fig. 1). The condition $\chi^{\mathrm{m}} = \sqrt{\delta}\,\chi^{\mathrm{r}}$ was satisfied by a proper choice of s.

4. Analysis of Test Results. Each experiment was performed in three steps.

1. The vertical σ_V^{m} and horizontal σ_H^{m} static stresses were chosen empirically to ensure a metastable state in the massif model [11], where slipping of one interblock joint R is close to the limiting value R_*, i.e., $R = R_* - \Delta R$, where $\Delta R \ll R_*$. The input H_1 and output H_2 holes in the tank T were open, and the pressure in the tank equaled the atmospheric value.

2. The oil-bed model was sealed, the pressure at the input hole H_1 was increased to $p_c^{\mathrm{m}} = p_0 + \Delta p^{\mathrm{m}}$ and was further sustained constant during the entire experiment. After that, the output hole H_2 was opened to reach the steady ($\dot{Q} = \mathrm{const}$) filtration mode, and the readings of the pressure probes P_j^0 were recorded.

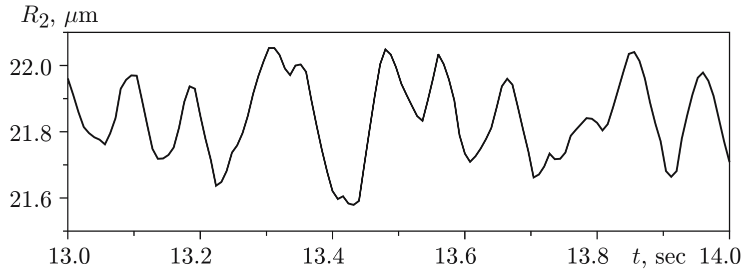

Fig. 4

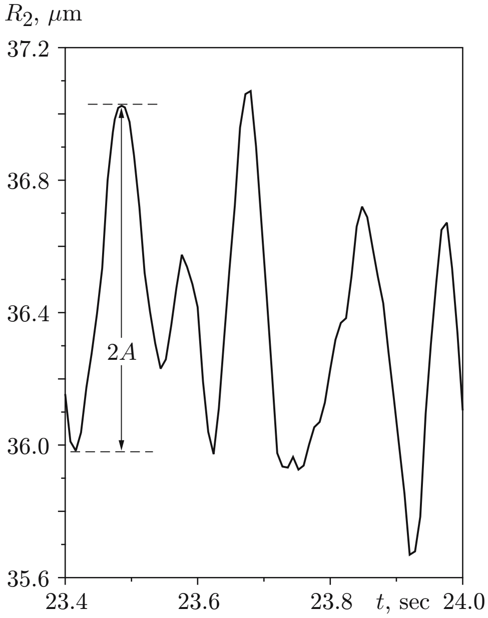

Fig. 5

3. An unsteady action with a very small displacement amplitude A insufficient to violate equilibrium of the system was applied to one of the blocks B_2–B_4. Then the amplitude A was gradually increased until the model acquired an unsteady state: the blocks started slipping.

The measurement equipment was triggered before increasing the amplitude; the recorded parameters were the dimensionless displacements $R_i(t)$ of the blocks B_i and B_{i+1}, the pressure $P_n(t)$ $(n = 1, 2, 3)$, and the flow rate $Q(t)$ in the output hole H_2.

Figure 3 shows the dimensionless displacements of the blocks. The initial static stresses were $\sigma_V^{\rm m} = 0.032$ MPa and $\sigma_H^{\rm m} = 0.012$ MPa, the pressure difference was $\Delta p^{\rm m} = 0.003$ MPa, $P_1^0 = 0.103$ MPa, $P_2^0 = 0.102$ MPa, and $P_3^0 = 0.1$ MPa. At the time $t = 0$, vibrations with a frequency $f^{\rm m} = 50$ Hz were applied to the block B_2; at $t = 3$ sec, its amplitude reached $A = 0.05$ μm, and the blocks started to slip; the dimensionless displacement R_2 exceeds the amplitude A by more than two orders of magnitude [a zoom-up of the curve $R_2(t)$ indicated by rectangle 1 in Fig. 3 is shown in Fig. 4]. The magnitude of slipping of the blocks decreases with distance from the block B_2: $|R_2| > |R_3| > |R_4|$ (see Fig. 3). Correspondingly, the influence of the blocks B_3 and B_4 on pressure in the oil bed also decreases, which agrees with the theoretical conclusion [11] that it is reasonable to implement the mechanism of stress redistribution by means of repacking of the system of blocks in the vicinity of oil-field areas with reduced pressure.

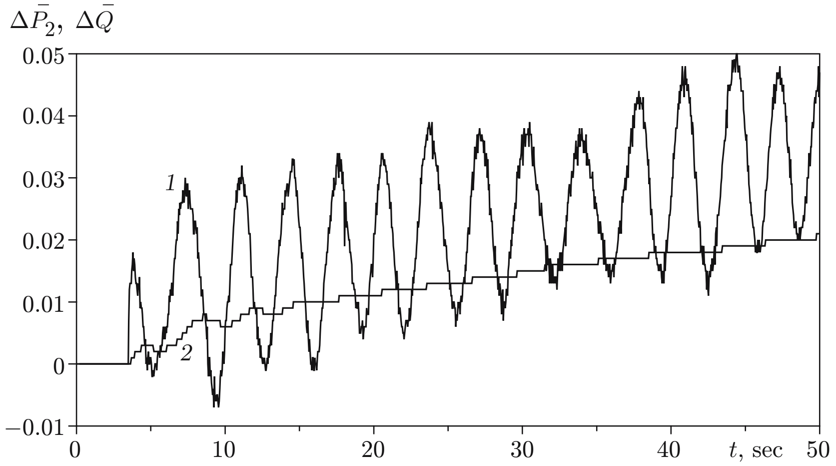

Fig. 6

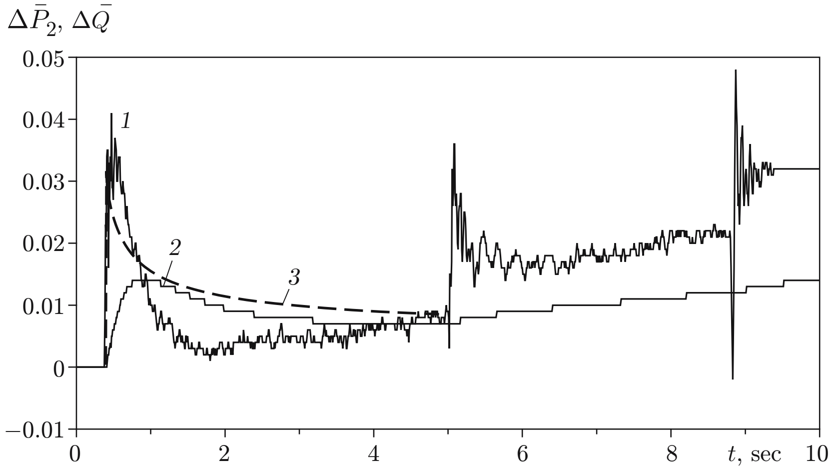

Fig. 7

Note that the displacement has a jumplike character: though the vibrations follow with the same amplitude (see Fig. 4), the values of R_i remain almost unchanged after slipping of the blocks. This can be interpreted as liberation of the "portion" of potential energy stored as a result of static loading.

The second step of the action of vibrations started at the time $t = 22$ sec: the amplitude A was increased, and a new displacement of the blocks occurred at $A = 0.5$ μm (see Fig. 3). It should be noted that the ratio $\max\limits_t |R_2(t)|/A$ was approximately equal to 440 in the first step of the action and to 170 in the second step [a zoom-up of the curve $R_2(t)$ indicated by rectangle 2 in Fig. 3 is shown in Fig. 5]. We can conclude that, to obtain a favorable effect under real conditions, the repeated unsteady treatment of one segment of the oil bed should be performed with a substantially increased power of the external action or after the block massif reaches a metastable state under the action of natural and man-induced factors, whose equilibrium can be violated by the power of available sources of disturbances.

Figure 6 shows the dimensionless changes in pressure $\Delta\bar{P}_2(t) = P_2(t)/P_2^0 - 1$ and flow rate $\Delta\bar{Q}(t) = Q(t)/(\dot{Q}_0 t) - 1$ (curves 1 and 2, respectively) in a system whose equilibrium (under unchanged static loads) is violated by vibrations with an amplitude $A = 0.5$ μm and frequency $f^{\rm m} = 50$ Hz. These quantities continue to increase, though only slightly (within 5%), after the vibrations are terminated.

Figure 7 shows the distributions of $\Delta\bar{P}_2(t)$ and $\Delta\bar{Q}(t)$ (curves 1 and 2, respectively) under the same test conditions but with a vertical pulsed load generating signals with an amplitude $A = 0.6$ μm and duration $t_0 \approx 0.02$ sec being applied to the block B_2. The residual effect is clearly expressed here: the time of pressure stabilization in the oil bed after shock loading exceeds t_0 at least by an order of magnitude. For comparison, curve 3 in the same figure shows the theoretical dependence $\Delta\bar{Q}(t)$ [11]. It has the same qualitative features as the experimental curve: elevated values in the beginning of the action and their decrease with time to a certain steady-state value.

Conclusions. It is experimentally demonstrated that rock massifs with a block structure can have metastable states whose equilibrium can be violated by a low-amplitude unsteady external action, which results in repacking of the system of blocks, redistribution of stresses, and increase in oil recovery.

A repeated repacking process can only be induced by an action with a severalfold higher amplitude than the initial value. This offers a possibility of deliberate unloading of stressed segments of rock massifs, aimed at reducing the danger of dynamic events.

This work was supported by the Russian Foundation for Basic Research (Grant No. 03-05-65350) and by Schlumberger Oilfield Services, an international company in the oil and gas industry.

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