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S. R. Rasulov[1], G. T. Hasanov[1], A. N. Zeynalov[2]

[1]Azerbaijan State Oil and Industry University, Baku, Azerbaijan Republic;
[2]SRI "Geotechnical problems of oil, gas and chemistry", Baku, Azerbaijan Republic.
E-mail: rasulovsakit@gmail.com

ACOUSTIC TESTING OF RHEOLOGICAL PROPERTIES OF OIL IN BOREHOLE

Abstract. The article considers the pulsed wave effect as more efficient and environmentally expedient in comparison with other influence methods. The effectiveness of the applied acoustic wave significantly depends on the correct choice of the mathematical model, taking into account the basic physical processes. When setting up mathematical model for removal of sand plug in bottom hole zone by acoustic influence it is necessary to consider variation of rheological parameters of oil versus depth. Physically, it means that it is necessary to study propagation of acoustic waves in non-homogeneous medium, as rheological parameters of fluid vary with depth. The problem in this statement has not been solved yet.

It was determined that particles of solids remaining in the well in suspension are in the gravitational field of the Earth and therefore, they are subject to the Boltzmann distribution over the depth of the well. In this case, the model proposed by Einstein for determining the viscosity of two-phase systems was used. The volume viscosity of oil changes when there is a particle of solids in it.

The dependence of changes in the rheological parameters of oil from the depth of the well mathematically comes down to solving the inverse problem for the equation proposed by Landau-Livshits. The inverse problem is to determine the desired value from the solution of the above equation with known information about the change in the acoustic waves of the front in time in two sections of the well.

Applying the Landau-Livshits model on the propagation of acoustic waves in a homogeneous fluid, a mathematical model of the propagation of acoustic waves in a heterogeneous fluid in oil wells is developed, where the rheological parameters of the fluid are subject to change at the changing of depth of borehole.

The hydrostatic pressure measurements in three drilling wells by depth gauges have shown that the deviation of the measured value of the hydrostatic pressure from the calculated to the depth of 2000-2500 m occurs according to linear law, after which there is a nonlinear law.

Based on the conducted researches of the diagnosis of rheological parameters of the fluid in the well, a graphical dependence of the change in relative density of oil on the depth of the well is constructed.

Key words: acoustic testing, rheology, oil, well, sand plug, acoustic waves, mathematical model.

Problem statement. Analysis of complications and emergency situations taking place while drilling and development of oil fields displays that many of them is related to variation of rheological parameters of oil [1,9]. Therefore, for the last years in order to avoid complications in production process, in particular to cleaning of bottom hole area from sand plug, the possibility of physical fields such as magnetic field, acoustic impact and others application is discussed in periodical press [1, 10-13]. We consider that pulsed wave effect is more efficient and environmentally appropriate for removal of sand plug from bottom hole area (the height of which constitutes 660000m each year) [14-16]. It is explained by exhaustion of layers in mature fields of Azerbaijan and due to this sand plug removal by traditional tools is not possible. That is why the repair works capacity each year involves over 100000 wells. The efficiency of applied acoustic wave field significantly depends on the correct choice of mathematical model taking into account the major physical processes.

When designing mathematical model of sand plug removal in bottom hole zone by use of acoustic effect the rheological parameters of oil variation versus depth must be taken into account. Physically this means the necessity to study propagation of acoustic waves in in homogeneous environment.

Therefore, the problem of bottom hole zone cleaning from sand plug by acoustic effect mathematically is reduced to resolution of equation of acoustic wave propagation in in homogeneous environment. It should be noted that the problem in such statement has not been solved.

Problem resolution. Various mathematical models are designed to describe acoustic waves propagation in the real fluid. For this case the Landau-Lipschitz model [1] is considered as appropriate:

$$\frac{\partial P}{\partial \alpha}=-\frac{1}{c}\frac{\partial P}{\partial t}+a(x)\frac{\partial^2 P}{\partial t^2}$$
$$a(x)=\frac{1}{2\rho c^3}\left[\left(\xi+\frac{4}{3}\eta\right)+k\left(\frac{1}{c_v}-\frac{1}{c_p}\right)\right] \tag{1}$$

where c – is acoustic wave propagation velocity; $\boldsymbol{P}$ – is field of acoustic pressure; η – is shearing viscosity; ξ – is bulk viscosity; ρ – is fluid density; c_{P} and c_{V} – are fluid heat absorption capacity at the constant pressure and capacity, respectively.

If acoustic pressure field is known, then from (1) we define the required value $a(x)$:

$$a(x)=\left(\frac{\partial P}{\partial x}+\frac{1}{c}\cdot\frac{\partial P}{\partial t}\right)\cdot\left(\frac{\partial^2 P}{\partial t^2}\right)^{-1} \tag{2}$$

In cases of unknown acoustic pressure field, it is required to derive the required $a(x)$ from resolution of equation (1).

Therefore, variation of rheological parameters of oil versus well depth is mathematically reduced to resolution of reverse problem for equation (1). The reverse problem consists in defining of $a(x)$ from solution of equation (1) in case of known variation of acoustic wave front in time at two sections of well.

Due to this the initial and boundary conditions are given as the following:

$$P(x,0)=0,\quad \frac{\partial P}{\partial t}(x,0)=0,\quad P(0,t)=\Phi(t),\quad P(\ell,t)=\varphi(t) \tag{3}$$

Resolving differential equation (1) applying Laplace transformation, we will have:

$$\frac{d\tilde{P}}{dx}=\left[-\frac{s}{c}+s^2 a(x)\right]\tilde{P};\qquad \tilde{P}(x,s)=\int_0^\infty P(x,t)\,e^{-st}dt \tag{4}$$

Applied conditions in (3) will be as the following:

$$\tilde{P}(0,s)=\tilde{\Phi}(s)=\int_0^\infty \Phi(t)e^{-st}dt;\quad \tilde{P}(\ell,s)=\tilde{\varphi}(s)=\int_0^\infty \varphi(t)e^{-st}dt \tag{5}$$

In the process of acoustic waves propagation in the fluid the compression and dilation of fluid takes place causing the second viscosity ξ, named as bulk viscosity.

Oil viscosity is evaluated according to data of testing of samples acquired at the output from well. These data on oil viscosity and rheological parameters in general do not correspond to parameters under real conditions.

The particles of solid bodies incoming from layer into the well are brought to the surface not in a whole amount. Particles of solid bodies left in well in suspended form are unevenly distributed along the hole depth. Their amount is maximal in bottom hole while it decreases towards well mouth. It can be regarded that solid body particles suspended in the well are the subject of Boltzmann distribution. If to match the origin of coordinates to the well mouth, then:

$$n = n_0\, exp(kx), \qquad \rho(x) = \rho_0\, exp(kx) \tag{6}$$

The viscosity coefficient for such two-phased fluids as crude oil can not be defined by the method applied for homogeneous fluids. Several rheological models exist for description of internal friction of oil. In case under the study it would be appropriate to use the model offered by Einstein for evaluation of viscosity of two-phase flow [17, 18]:

$$\eta = \eta_0(1 + 2{,}5n) \tag{7}$$

where η_0 – is viscosity of pure fluid; n – is ratio of particles of hard bodies volume to total volume of fluid in the well.

Taking into account formula (6), the formula (7) is written as below

$$\eta = \eta_0\left(1 + 2{,}5n_0 e^{kx}\right) \tag{8}$$

Similar to shear viscosity the bulk viscosity ξ of oil varies in case of solid body particles presence. Variation of bulk viscosity due to the presence of particles of solid bodies is calculated by Brenner [3] and is in the form shown below:

$$\xi = \xi_0\left[1 + n_0\left(1 + \frac{4}{3}\cdot\frac{\eta_0}{\xi_0}\right)e^{kx}\right] \tag{9}$$

The constant coefficient «*k*» in formulae (6), (8) and (9) characterizes variation degree of ρ, η, ξ from point to point versus variation of well depth and is a measure of diagnosis. It must be noted that for fluids $c_p \approx c_v$ and therefore

$$a(x) = \frac{1}{2\rho c^3}\left(\xi + \frac{4}{3}\cdot\eta\right) = \alpha_0\cdot e^{kx} + \beta_0 \tag{10}$$

$$\alpha_0 = \frac{1}{2\rho_0 c^3}\left(\xi_0 + \frac{4}{3}\cdot\eta_0\right); \qquad \beta_0 = \frac{1}{2\rho_0 c^3}\left[\xi_0 n_0\left(1 + \frac{4}{3}\cdot\frac{\eta_0}{\xi_0}\right) + \frac{4}{3}\cdot\eta_0\cdot 2{,}5n_0\right]$$

Resolution of equation (4) while boundary conditions (5) is as the following:

$$\tilde{\phi}(s) = \tilde{\Phi}(s)\exp\left\{-\frac{s}{c}\ell + s^2\left[\beta_0\ell + \frac{\alpha_0}{k}\left(1 - e^{-k\ell}\right)\right]\right\} \tag{11}$$

To define «*k*» from equation (11) we apply the method of determined moments. For this, we expand the functions $\tilde{\phi}(s)$ and $\tilde{\Phi}(s)$ in series by degrees of s , i.e.:

$$\tilde{\phi}(s) = \phi_0 + s\phi_1 + s^2\phi_2 + \ldots \quad ; \quad \tilde{\Phi}(s) = \Phi_0 + s\Phi_1 + s_2^2\Phi_2 + \ldots \tag{12}$$

While φ_n and Φ_n are derived from the following:

$$\phi_n = \int_0^\infty\left[\phi_n(\tau) - \phi_\infty\right]\frac{\tau^n}{n!}d\tau; \qquad \Phi_n = \int_0^\infty\left[\Phi_n(\tau) - \Phi_\infty\right]\frac{\tau^n}{n!}d\tau \tag{13}$$

Substituting (12) in (11) to define «*k*» by diagnostic measure we derive transcendental equation:

$$\frac{\alpha_0}{k}\left(1 - e^{-k\ell}\right) = \frac{\phi_2}{\Phi_0} - \frac{1}{2}\left(\frac{\Phi_1}{\Phi_0} - \frac{\phi_1}{\Phi_0}\right)^2 + \frac{\Phi_1}{\Phi_0}\left(\frac{\Phi_1}{\Phi_0} - \frac{\phi_1}{\Phi_0}\right) - \frac{\Phi_2}{\Phi_0} - \beta\ell \tag{14}$$

Taking into account that $k\ell < 1$, expand $exp(-k\ell)$ in series and we are restricted by initial three expansion terms. While doing this we have:

$$k = \frac{2}{\ell}\left\{1 - \frac{1}{\alpha_0 \ell}\left[\frac{\phi_2}{\Phi_0} - \frac{1}{2}\left(\frac{\Phi_1}{\Phi_0} - \frac{\phi_1}{\Phi_0}\right)^2 + \frac{\Phi_1}{\Phi_0}\left(\frac{\Phi_1}{\Phi_0} - \frac{\phi_1}{\Phi_0}\right) - \frac{\Phi_2}{\Phi_0} - \beta\ell\right]\right\} \tag{15}$$

At present it is considered as complicated to hold direct experiments to study acoustic wave front variation versus time in two deep oil wells. Due to this we have limited our studies by indirect, experimental data evidencing necessity to test rheological parameters of oil along well depth.

The oscillogram of acoustic wave front for two oil samples acquired from various depths of active wells in “Neft dashlary” field is shown in figure 1.

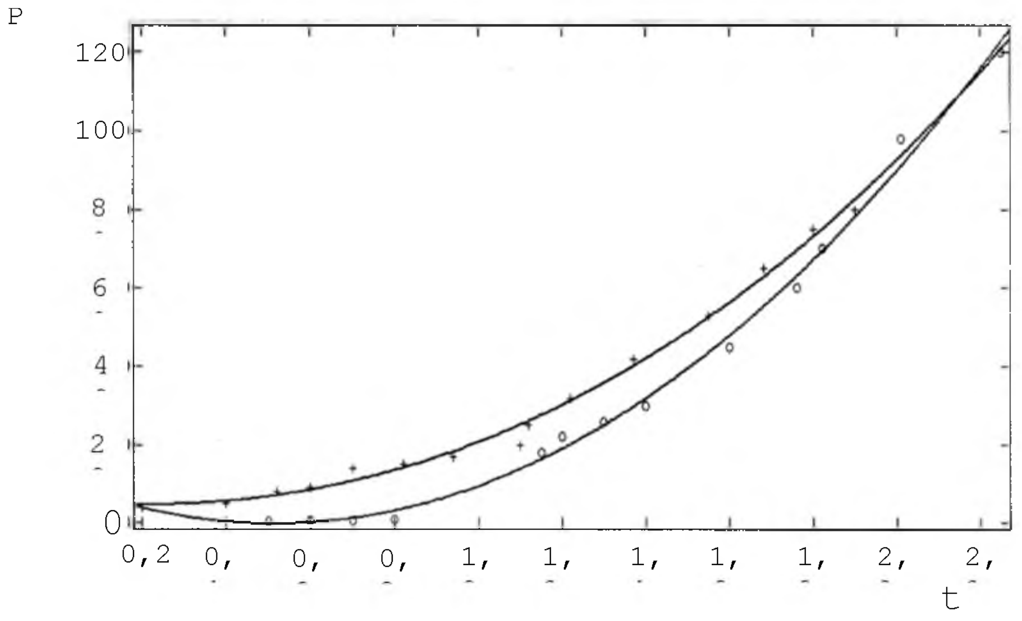

Figure 1 – Acoustic wave variation versus time

Computer processing of testing data displayed that these curves can be described by formulae below:

$$\Phi(t) = A_1 t\, exp\left(-B_1 t^2\right), \qquad \varphi(t) = A_2 t\, exp\left(-B_2 t^2\right) \tag{16}$$

Rheological parameters of studied oil samples, according to laboratory testing were as the following: ρ_o = 780 kg/m^3, η_o = 0,002 Pa·c, ρ_o = 820 kg/m^3, η_o = 0.003 Pa·c. Bulk viscosity value ξ_o has been evaluated as equal to the shear viscosity η_o.

Oil samples were acquired from the depths 2200 m and 3500 m. Computing solution of equation (14) taking into account processing results of tests [19] according to “MATLAB” software allowed us to define the average value of $k = 1.25{\cdot}10^{-4}\,\mathrm{m}^{-1}$.

To define the degree of correspondence of calculated value of «k» to reality we have measured in-situ the hydrostatic pressure by depth gauge while drilling of oil well in “Neft Dashlary” field.

Hydrostatic pressure measured by depth gauge in three wells displayed that down to 900-1000 m depths the hydrostatic pressure values are approximately coincide with those calculated according to formula $P = \rho_0 gH$, where ρ_0 – is the density of drilling mud at output.

At depths below than 900-1000 m the discrepancy is observed between calculated and measured values of hydrostatic pressure. Processing of hydrostatic pressure values measured down to 2000-2500 m depths showed that measured hydrostatic pressure value can be accurately defined by the formula below [20]:

$$P = \rho_o gH\,(1 + kH) = P_o\,(1 + kH) \tag{17}$$

where g - is acceleration of free pressure, $k \approx 2{\cdot}10^{-4}\,\mathrm{m}^{-1}$.

Starting from depths of 2000-2500 m the deviation of measured hydrostatic pressure from calculated value corresponds to quadratic law, i.e. the non-linear law.

Formula (17) represents the sum of initial two expansion terms in series of more general formula, $k \ll 1$:

$$P = P_o \, exp(kH), \qquad \rho = \rho_o \, exp(kH) \tag{18}$$

Derived average value of the constant «*k*» corresponds to the value of diagnosing measure calculated according to the proposed algorithm.

The diagram below (figure 2) is drawn on the basis of studied rheological parameters of fluid in the well.

Based on these theoretical and experimental studies we may derive the following **conclusions**:

– it has been established that the particles of solid bodies left in well in a suspended condition are distributed unevenly along the borehole depth. Concentration of these particles increases with depth;

– hydrostatic pressure values measured in wells under the drilling are almost coincide for depths down to 900-1000 m with those calculated according to formula $P = \rho_0 gH$, where ρ_0 is density of drilling mud at well output;

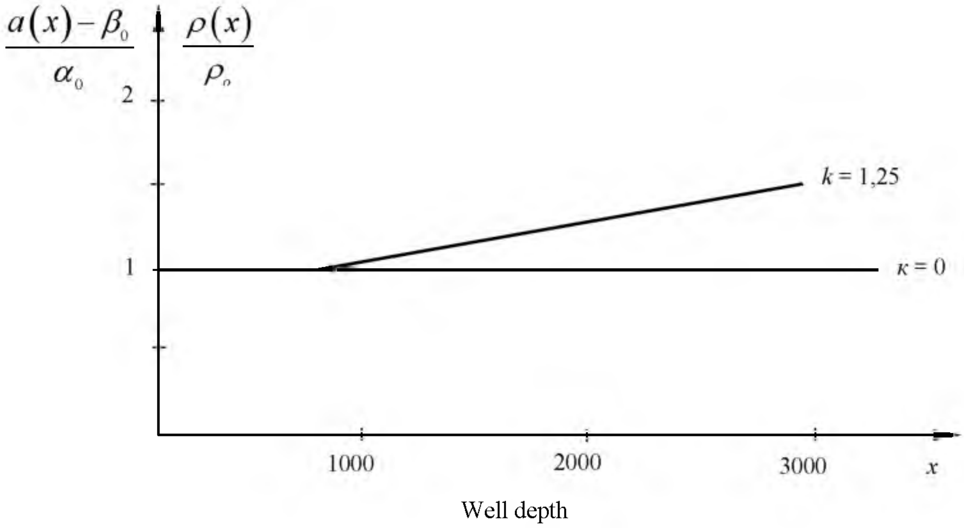

Figure 2 – Relative density of oil variation versus well depth

– starting from 900 – 1000 m depths and below the measured hydrostatic pressure values deviate from calculated values. Hydrostatic pressure measured in three wells under the drilling process displayed that deviation of measured hydrostatic pressure value from calculated value down to 2000-2500m takes place according to linear law;

– particles of solid bodies left in well in a suspended condition are in the gravity field of Earth and therefore they are the subject of Boltzmann distribution along the depth of borehole;

– applying Landau-Lipschitz model of acoustic waves propagation in homogeneous fluid the mathematical model of acoustic waves propagation in inhomogeneous fluid has been developed for oil wells where rheological parameters of fluid vary with depth.

С. Р. Расулов[1], Г. Т. Гасанов[1], А. Н. Зейналов[2]

[1]Әзірбайжан мемлекеттік мұнай және өнеркәсіп университеті, Баку, Әзірбайжан;
[2]«Мұнай, газ және химияның геотехнологиялық мәселелері» ҒЗИ, Баку, Әзірбайжан

МҰНАЙ ҰҢҒЫМАСЫНДАҒЫ РЕОЛОГИЯЛЫҚ МЕНШІКТЕРДІҢ АКУСТИКАЛЫҚ ДИАГНОСТИКАСЫ

Аннотация. Мақалада ұңғыма түбіндегі құм тығындыларының аймағын тазартуға арналған импульсті толқын әрекеті басқа әсер ету әдістерімен салыстырғанда тиімдірек және экологиялық таза екендігі көрсетілген. Қолданылатын акустикалық толқындық әсердің тиімділігі негізгі физикалық процестерді ескере отырып, математикалық үлгіні дұрыс таңдауга байланысты болады. Ұңгыма түбіндегі құм тыгындыларының аймағын акустикалық әсермен жоюдың математикалық моделін құрастыру кезінде ұңгыманың тереңдігімен байланысты мұнайдың реологиялық параметрлерінің өзгеруін ескеру қажет. Физикалық тұргыдан алганда, бұл біртектес емес ортадагы акустикалық толқындардың таралуын зерттеу керек екенін білдіреді. Ұңгымадағы мұнайдың реологиялық параметрлері тереңдікке байланысты өзгереді. Айта кетейік, бұл мәселе мұндай тұжырымда шешілмеген.

Ұңгымада суспензияда қалган қатты заттар Жердің тартылыс өрісінде болатындыгы анықталды, сондықтан олар ұңгыманың тереңдігі бойынша Больцманга таралуы керек. Қарастырылган жағдайда Эйнштейн ұсынган модель екі фазалы жүйелердің тұтқырлығын анықтауга арналған. Майдың көлемді тұтқырлыгы қатты денелерде болган кезде өзгереді.

Мұнайдың реологиялық параметрлері өзгерісінің ұңгыманың тереңдігіне тәуелділігі Ландам - Лифшиц ұсынган теңдеу үшін кері есепті шешуге математикалық түрде азаяды. Кері мәселе жогарыда келтірілген теңдеудің шешімінен құдықтың екі учаскесінде уақытында акустикалық толқынның алдын-ала өзгеруі туралы белгілі ақпараттармен керекті шаманы анықтау болып табылады.

Ландау-Ливщиц моделін біртекті сұйықтықта акустикалық толқындардың таралуында қолдана отырып, мұнай ұңгымаларында гетерогенді сұйықтықта акустикалық толқындардың таралуының математикалық моделі жасалды, мұнда сұйықтықтың реологиялық параметрлері ұңгыманың тереңдігінің өзгеруімен өзгеруі керек.

Терең манометрлермен бұргыланған ұңгымалардағы гидростатикалық қысымды өлшеу гидростатикалық қысымның есептелген мәнінен 2000-2500 м тереңдікке ауытқуы сызықтық заңга сәйкес жүретінін, содан кейін сызықтық емес заң пайда болатындыгын көрсетті.

Ұңгымадағы сұйықтықтың реологиялық параметрлерін диагностикалау зерттеулерінің негізінде мұнайдың салыстырмалы тыгыздыгы өзгерісінің ұңгыманың тереңдігіне графикалық тәуелділігі құрылды.

Түйін сөздер: акустикалық диагностика, реология, мұнай, ұңгыма, құм ашасы, акустикалық толқындар, математикалық модель.

С. Р. Расулов[1], Г. Т. Гасанов[1], А. Н. Зейналов[2]

[1]Азербайджанский государственный университет нефти и промышленности, Баку, Азербайджан;
[2]НИИ «Геотехнологические проблемы нефти, газа и химия», Баку, Азербайджан

АКУСТИЧЕСКОЕ ДИАГНОСТИРОВАНИЕ РЕОЛОГИЧЕСКИХ СВОЙСТВ НЕФТИ В СКВАЖИНЕ

Аннотация. В статье показано, что импульсное волновое действие для очистки призабойной зоны от песчаной пробки является более эффективным и экологически целесообразным по сравнению с другими методами воздействия. Эффективность применяемого акустического волнового воздействия существенно зависит от правильного выбора математической модели с учетом основных физических процессов. При составлении математической модели ликвидации песчаной пробки в призабойной зоне акустическим воздействием необходимо учесть изменение реологических параметров нефти, связанных с глубиной скважины. Физически это означает, что необходимо исследовать распространение акустических волн в неоднородной среде, так как реологические параметры нефти в скважине изменяется с изменением глубины. Отметим, что этот вопрос в такой постановке не решён.

Определено, что частицы твердых тел, оставшихся в скважине во взвешенном состоянии, находятся в поле тяготения Земли и поэтому по глубине скважины они подчиняются распределению Больцмана. В рассматриваемом случае использовалась модель, предложенная Эйнштейном для определения вязкости двухфазных систем. Объемная вязкость нефти изменяется при наличии в ней частицы твердых тел.

Зависимость изменения реологических параметров нефти от глубины скважины математически сводится к решению обратной задачи для уравнения, предложенного Ландау-Лифшицам. Обратная задача заключается в определении искомой величины из решения вышеуказанного уравнения при известных информациях об изменении фронта акустической волны во времени на двух сечениях скважины.

Применяя модель Ландау-Ливщиц о распространении акустических волн в однородной жидкости, разработана математическая модель распространения акустических волн в неоднородной жидкости в условиях нефтяных скважин, где реологические параметры жидкости подлежат изменению при изменении глубины скважины.

Измерения гидростатического давления в трех бурящихся скважинах глубинными манометрами показали, что отклонение измеренного значения гидростатического давления от вычисленного до глубины 2000-2500 м происходит по линейному закону, после чего имеет место нелинейным закон.

На основании проведенных исследований диагностирования реологических параметров жидкости в скважине построена графическая зависимость изменения относительной плотности нефти от глубины скважины.

Ключевые слова: акустическое диагностирование, реология, нефть, скважина, песчаная пробка, акустические волны, математическая модель.

Information about authors:

Rasulov Sakit Rauf, doctor of technical sciences, professor, head of the department, Azerbaijan State Oil and Industry University, Baku, Azerbaijan Republic; rasulovsakit@gmail.com; https://orcid.org/0000-0002-1548-3143

Hasanov Ghafar Teymur, doctor of physical and mathematical sciences, professor, Azerbaijan State Oil and Industry University, Baku, Azerbaijan Republic; gasanov_1940@mail.ru; https://orcid.org/0000-0002-3132-5524

Zeynalov Anar Naib, candidate of technical sciences, SRI "Geotechnical problems of oil, gas and chemistry", Baku, Azerbaijan Republic; anar.zeynalov13@hotmail.com; https://orcid.org/0000-0002-4872-7255

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