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STRESS-STRAIN STATE OF COAL WELLS KARAGANDA BASIN

The article considers the problem of determining the thermoelastic stresses that arise when drilling a coal seam with a depth of at least 800 m. The stress-strain state is a term that has penetrated from the mechanics of a deformable solid body into various areas, both natural and technological. Usually, three types of stress-strain state are distinguished: the first type of elastic work - up to 35% of the breaking load; the second type of elastic-plastic work - up to 75% of the breaking load, while cracks appear and their number increases with increasing load; the third type of destruction - cracks appear like an avalanche and every detail is destroyed. For the first time, we succeeded in solving analytically the Stefan problem for a cylinder of finite dimensions, with a moving interface, by selecting an integral transformation.

A similar solution for a well in coal seams (as well as for other applications) gives an analytical solution to the deformation-wave process in a rock mass, discovered experimentally in the late 70s of the last century (scientific discovery of 1985, priority of 1978). Our experimental and theoretical results fit into the model of macroscopic localization of plastic flow. This model shows that the localization of plastic flow in solids (and in a coal seam) has a pronounced wave character. At the same time, at the stages of easy slip, linear and parabolic strain hardening, as well as at the stage of preliminary destruction, the observed patterns of localization are different types of wave processes.

Key words: coal seam, well, Stefan problem, stresses, temperature, depth, wave process.

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Қарағанды бассейннің көмір ұңғымаларының кернеулі-деформациялық күйі

Мақалада кемінде 800 м тереңдіктегі көмір қабатын бұрғылау кезінде пайда болатын термосерпімді кернеулерді анықтау мәселесі қарастырылған. Әдетте кернеулі-деформациялық күйдің үш түрін ажыратылады: серпімді жұмыстың бірінші түрі – үзілу жүктемесінің 35% дейін; серпімді-пластикалық жұмыстың екінші түрі – сыну жүктемесінің 75% -на дейін, бұл кезде жарықтар пайда болады және жүктеменің өсуімен олардың саны артады; үшінші бұзылу түрі – қар көшкіні сияқты жарықтар пайда болады және әрбір бөлшек бұзылады. Біз алғаш рет интегралды түрлендіруді таңдау арқылы қозғалатын интерфейсі бар соңғы өлшемді цилиндрге арналған Стефан есебін аналитикалық жолмен шешуге қол жеткіздік.

Көмір қабаттарындағы ұңғымаға арналған ұқсас шешім (басқа қолданбалар сияқты) өткен ғасырдың 70-жылдарының соңында эксперименттік түрде ашылған тау-кен массасындағы деформация-толқын процесінің аналитикалық шешімін береді (1985 жылғы ғылыми жаңалық, басымдық 1978). Біздің тәжірибелік және теориялық нәтижелер пластикалық ағынның макроскопиялық локализациясының моделіне сәйкес келеді. Бұл модель қатты денелерде (және көмір қабатында) пластикалық ағынның локализациясы айқын толқындық сипатқа ие екенін көрсетеді. Сонымен қатар жеңіл сырғанау, сызықтық және параболалық деформацияның шыңдалуы кезеңдерінде, сондай-ақ алдын ала жойылу сатысында локализацияның байқалатын заңдылықтары толқындық процестердің әртүрлі типтері болып табылады.

Түйін сөздер: көмір қабаты, ұңғыма, Стефан мәселесі, кернеулер, температура, тереңдік, толқындық процесс.

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Напряженно-деформированное состояние угольных скважин карагандинского бассейна

В статье рассмотрена задача об определении термоупругих напряжений, возникающих при бурении угольного пласта глубиной не менее 800 м. Напряженно-деформированное состояние – это термин, который из механики деформируемого твердого тела проник в различные сферы, как природного, так и технологического типа. Обычно, различают три типа напряженно-деформированного состояния: первый тип упругой работы – до 35% от разрушающей нагрузки; второй тип упруго-пластической работы – до 75% от разрушающей нагрузки, при этом возникают трещины и их число растет с увеличением нагрузки; третий тип разрушение – трещины возникают лавинообразно и всякая деталь разрушается.

Нам впервые удалось путем подбора интегрального преобразования решить аналитически задачу Стефана для цилиндра конечных размеров, с подвижной границей раздела фаз. Подобное решение для скважины в угольных пластах (а также для других приложений) дает аналитическое решение деформационно-волновому процессу в массиве горных пород, открытое экспериментально в конце 70-х годов прошлого века (научное открытие 1985 года приоритет 1978 года). Полученные нами экспериментальные и теоретические результаты укладываются в модель макроскопической локализации пластического течения. В этой модели показано, что локализация пластического течения в твердых телах (и в угольном пласте) имеет ярко выраженный волновой характер. При этом на стадиях легкого скольжения, линейного и параболического деформационного упрочнения, а также на стадии предварительного разрушения наблюдаемые картины локализации суть разные типы волновых процессов.

Ключевые слова: угольный пласт, скважина, задача Стефана, напряжения, температура, глубина, волновой процесс

Introduction

This article is considered a continuation of the work [1], where the extraction of methane from a coal seam was considered. Here we also propose a theory of microcrack formation (which refers to condensed matter physics) in wells drilled from the surface. They are formed during well drilling due to the occurrence of the stress-strain state of the coal seam, as well as due to its hydraulic fracturing [2].

The stress-strain state (SSS) is a term that, from the mechanics of a deformable solid body, has penetrated into various areas, both natural and technological types [3]. Usually, 3 types of SSS are distinguished: the first type of elastic work - up to 35% of the breaking load; the second type of elastic-plastic work - up to 75% of the breaking load, while cracks appear and their number increases with increasing load; the third type of destruction - cracks appear like an avalanche and every detail is destroyed. Works [4–6] are devoted to this issue. See also the bibliography presented in these works. SSSs are also classified according to loads [3]: by the nature of occurrence, which include technological, atmospheric, own weight of load-bearing and enclosing structures, seismic, explosive effects, fire, soil subsidence; according to the duration of the load: constant (dead weight, soil pressure, prestress); long-term (weight of stationary equipment on ceilings; pressure of gases, liquids, bulk solids; long-term part of crane, snow loads, etc.); short-term (short-term part of crane, snow loads, wind loads); special (seismic, explosive impacts, equipment failure, subsidence of foundations).

In this article, we will consider SSS in wells. They were drilled from the surface to a depth of more than 800 m. The difference from the above works is that the drilling process is considered as a process with a moving interface (due to drilling). This problem was first proposed by J. Stefan (1889) when considering the freezing of ice in a reservoir by solving the problem of heat conduction. A large number of works, dissertations, monographs, etc. are devoted to Stefan's problem. We will only mention a few of them to clarify the essence of the issue. The work [7] contains a survey on the Stefan problem, which includes 339 papers on this problem. The work [8] contains a critical review of a large number of works. The last review of papers on the Stefan problem is given in [9]. From a mathematical point of view, boundary value problems of this type are fundamentally different from classical problems of heat conduction. Due to the dependence of the size of the flow transfer region on time, the classical methods of separation of variables and integral Fourier transforms are inapplicable to this type of problems, since, remaining within the framework of the classical methods of mathematical physics, it is not possible to coordinate the solution of the equation with the motion of the phase boundary. Numerical modeling of Stefan problems is considered in [10-12]. In [13, 14], we managed to choose an integral transformation and solve for the first time the Stefan problem for a finite cylinder (this problem was previously solved for an infinite cylinder). Subsequently, this work was used by metallurgists in calculating the crystallization of a steel ingot.

The development in the 2000s of directional drilling with horizontal sections up to 3-4 kilometers long, together with multi-stage hydraulic fracturing, made it possible to start economically viable production of gas, and then light oil, from tight reservoirs from shale formations [15].

In the Karaganda coal basin, such drilling has begun quite recently and is reflected in the dissertation [16]. The coal seams of the Karaganda coal basin have very low gas permeability and gas recovery parameters, which does not allow underground degassing to ensure the safety of miners' work as reliably as possible. The extraction of methane gas by drilling directional wells will reduce the natural gas content of coal seams and increase the productivity of mining operations during coal mining [17].

Materials and Methods

Directional drilling is a rotary drilling method with flushing with polymer mud. At the end of drilling, casing string 1 is installed (Figure 1) [16]. Upon completion of the descent of the column, the annulus is plugged with cement mortar.

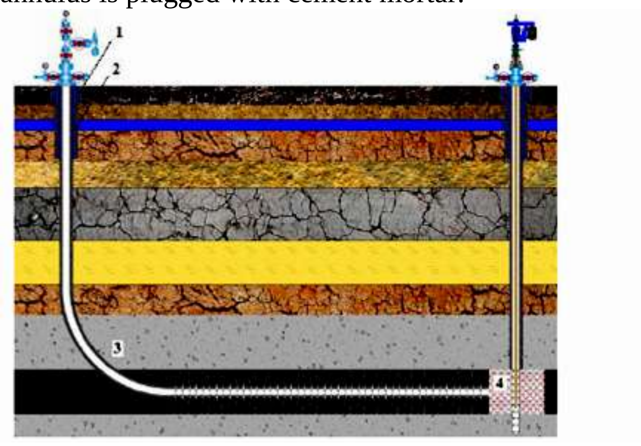

Figure 1. The developed technology for extracting methane from coal seams of the Karaganda basin [16].

When drilling under the conductor, the rotary method of drilling with flushing with polymer drilling fluid is also used. At the end of drilling of this interval, it is planned to install conductor 2 (Fig. 1), with steel casing pipes, in order to protect the subsoil and preserve aquifers, the conductor is cemented to the mouth. To drill in a coal seam, we need to enter the coal seam at the angle of the coal seam 3 (Fig. 1). The angle will be set using a screw downhole motor. The development of a well with pumping out of the working fluid and gas is carried out through a vertical well, previously drilled from the surface to the productive formation, the bottom of which is aligned with the directional cavity formed as a result of the expansion of the walls of the well 4 (Fig. 1). In the process of drilling, as well as using hydraulic fracturing with polymer drilling fluids, microcracks are formed in the coal seam, through which methane flows (Fig. 2). Our task is to construct a theoretical model of the development of these microcracks in order to give a way to extract methane from coal seams.

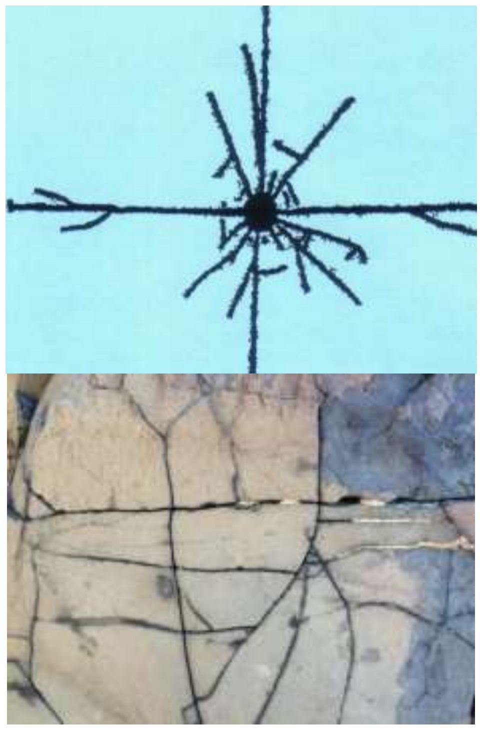

Figure 2. Microfractures in a coal seam.

Research methods

The components of thermoelastic stresses along the radius r is σ_r and along the axis z - σ_z is of the coal seam in the well will be estimated using the known equations [18]:

$$\sigma_r = -2G\frac{1}{r}\frac{\partial T}{\partial r}, \quad (1)$$

$$\sigma_z = -2G\frac{1}{r}\frac{\partial T}{\partial z}, \quad (2)$$

here, the shear modulus *G* is given by:

$$2G = \frac{E}{1+\varepsilon}, \quad (3)$$

where *E* is Young's modulus, ε is Poisson's ratio.

From equations (1) and (2) we need to determine the temperature gradients in order to calculate the stresses in the well when the drilling process is in progress.

The non-stationary heat equation in a moving cylindrical coordinate system moving according to the law $\beta(t)$ has the form:

$$\frac{\partial T}{\partial t} = \ddot{A}\left[\frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right], \quad (4)$$

where $\ddot{A}$ is the coefficient of thermal diffusivity. We choose the initial and boundary conditions in the general form:

$$T(r,z,t)|_{t=0} = \varphi(r,z),$$
$$T(r,z,t)|_{t=R} = \gamma(z,t),$$
$$T(r,z,t)|_{z=0} = \gamma_1(r,t),$$
$$T(r,z,t)|_{z=\beta(t)} = \gamma_1(r,t).$$

The general solution was given by us in [13, 14] and looks like this:

$$T(r,z,t) = \sum_{\hat{e}=0}^{\infty} J_0(\lambda_{\hat{\imath}\hat{e}} r)\left\{e^{-\ddot{A}t}\left[\frac{1}{2\ddot{A}\sqrt{\pi}}\int_0^t e^{\frac{(z-\xi)^2}{4\ddot{A}t}}dt\ * \right.\right.$$
$$*\left(\int_0^l \varphi(r,\xi) I_0(\lambda_{0k} r) r dr\right) d\xi +$$
$$+\frac{R I_1(\lambda_{0k} R)}{2\sqrt{\pi}\ddot{A}}\int_0^t d\tau \int_0^l \frac{\gamma(\xi,\tau)}{\sqrt{t-\tau}} e^{-\ddot{A}t} e^{-\frac{(z-\xi)^2}{4\ddot{A}(t-\tau)}} d\xi +$$
$$\left.+\frac{1}{4\sqrt{\pi}}\int_0^t \frac{z-\beta(z)}{\left[\ddot{A}(t-\tau)\right]^{3/2}} e^{-\frac{[z-\beta(z)]^2}{4\ddot{A}(t-\tau)}} K_2(\tau) d\tau\right\}. \quad (5)$$

To use Eqs (1)-(3), we simplify the general problem (5) by taking homogeneous boundary conditions. In this case:

$$\frac{\partial T}{\partial t} = \ddot{A}\left[\frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial x}\right)\right], \quad (6)$$

$$\left.\begin{aligned} T(r,z,t)|_{t=0} &= 0; \\ T(r,z,t)|_{r=R} &= T_0 = const; \\ T(r,z,t)|_{z=0} &= T_0 = const; \\ T(r,z,t)|_{z=\beta(t)} &= T_0 = const \end{aligned}\right\}, \quad (7)$$

where T_0 is the temperature value on the cylinder surface and on the moving media interface. Then the general solution of the problem takes the form:

$$T(r,z,t) =$$
$$= \sum_{\hat{e}=0}^{\infty} I_0(\lambda_{0\hat{e}} r)\left\{e^{-\ddot{A}t}\left[\frac{R I_1(\lambda_{0\hat{e}} R)}{2\sqrt{\pi\ddot{A}}}\int_0^t d\tau \int_0^H \frac{\widetilde{N}_1}{\sqrt{t-\tau}} * \right.\right.$$
$$* e^{-\ddot{A}t} e^{-\frac{(z-\xi)^2}{4\ddot{A}(t-\tau)}} d\xi +$$
$$+\frac{1}{4\sqrt{\pi}}\int_0^t \frac{z}{\left[\ddot{A}(t-\tau)\right]^{3/2}} e^{-\frac{z^2}{4\ddot{A}(t-\tau)}} K_1(\tau) d\tau +$$
$$\left.\left.+\frac{1}{4\sqrt{\pi}}\int_0^t \frac{z-\beta(z)}{\left[\ddot{A}(t-\tau)\right]^{3/2}} e^{-\frac{[z-\beta(z)]^2}{4\ddot{A}(t-\tau)}} K_2(\tau) d\tau\right]\right\}. \quad (8)$$

For a stationary temperature, we have the following expression:

$$T(r,z) = \frac{T_0 R}{\sqrt{\pi} z} I_0\left(\frac{2r}{R}\right). \quad (9)$$

When obtaining (8), we took into account that from the equation $I_0(\lambda_{0r})=0$ it follows that $\lambda_0 = 2r/R$ and $I_1(2) = 1$. The radial and axial components of the temperature gradient, taking into account (9), will be equal to

$$\frac{\partial T}{\partial r} = \frac{2}{z}\frac{T_0}{\sqrt{\pi}} I_1\left(\frac{2r}{R}\right), \quad (10)$$

$$\frac{\partial T}{\partial z} = \frac{R T_0}{\sqrt{\pi} z^2} I_0\left(\frac{2r}{R}\right). \quad (11)$$

The radial and axial stress components have the form:

$$\sigma_r = -2G\frac{1}{r}\frac{\partial T}{\partial r} = -\frac{4}{\sqrt{\pi}}\cdot\frac{G T_0}{r z} I_1\left(\frac{2r}{R}\right), \quad (12)$$

$$\sigma_z = -2G\frac{\partial T}{\partial z} = -\frac{2}{\sqrt{\pi}}\cdot\frac{G R T_0}{z^2} I_0\left(\frac{2r}{R}\right). \quad (13)$$

Results and discussion

Let us first discuss the solutions obtained in equations (12) and (13). The radial and axial stress components depend on the Bessel functions. Our experimental and theoretical results fit into the model of macroscopic localization of plastic flow developed in [19]. In this work, it is shown that the localization of plastic flow in solids (and in a coal seam) has a pronounced wave character. At the same time, at the stages of easy slip, linear and parabolic strain hardening, as well as at the stage of preliminary destruction, the observed patterns of localization are different types of wave processes. An analysis of the wave characteristics of such processes made it possible to measure their propagation velocity ($\sim 10^{-4}$ m/s), wavelength ($\sim 10^{-2}$ m) and establish that the dispersion relation for such waves has a quadratic character. The Bessel functions obtained in equations (12) and (13) in the well are shown in fig. 3a and they describe a periodic wave process.

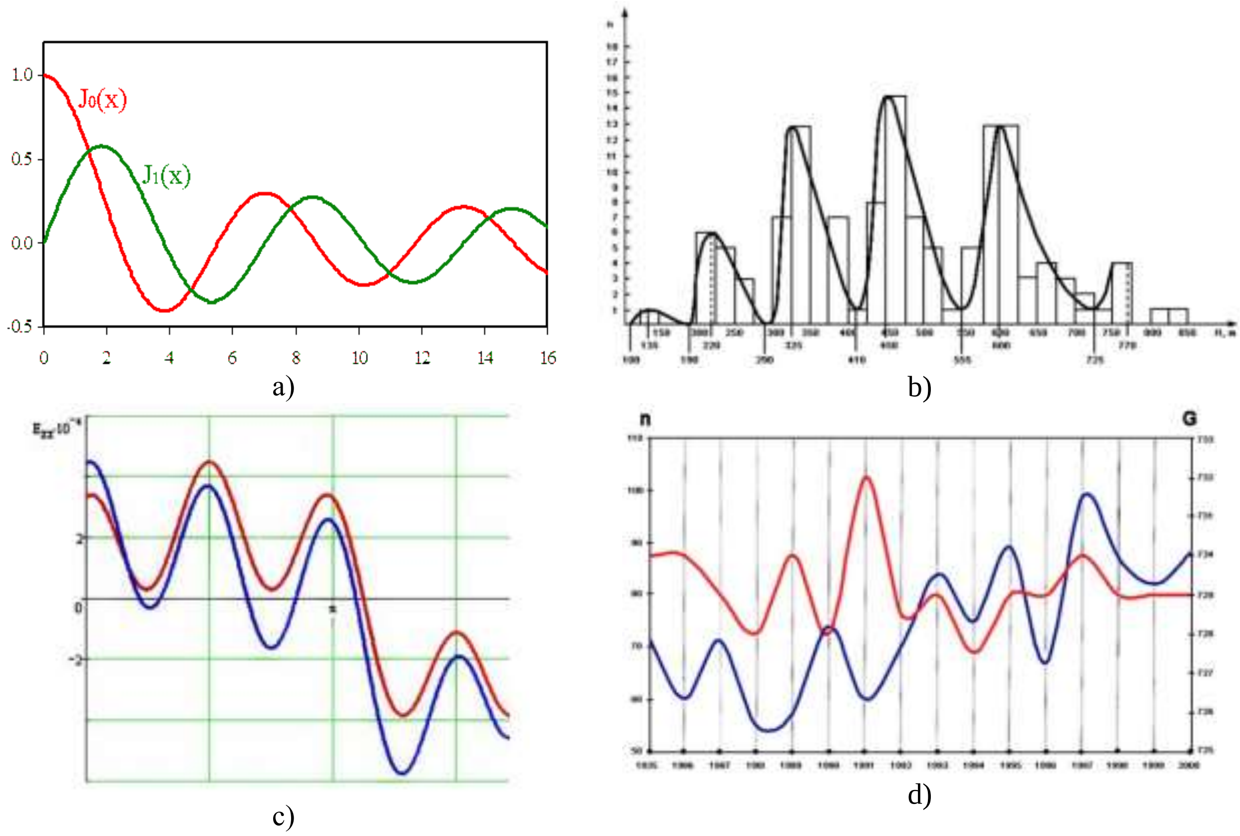

Figure 3. The Bessel functions obtained in equations (12) and (13) in the well

On fig. 3b shows [20] that the magnitude of rock bumps periodically changes with depth from the surface. It turns out that the thickness of coal seams appears to be differentiated by different zones, in which the structure of its states changes when changing from one area to another.

On fig. 3c shows [21] that a comparison of longitudinal and transverse deformations of highly compressed rocks also showed their periodic character. This character arises within the framework of the model of a defective medium, in which the stresses are determined by the field of mesic cracks interacting with each other at the boundaries of mineral grains.

On fig. 3d shows [22] that the magnitudes of variations in the gravitational constant (red line) and seismic activity (blue line) of the globe also have a wave character, since our Earth is subjected to gigantic compressive stresses that cause earthquakes.

Equations (5), (12) and (13) are solved on modern computers simply taking into account even in a general form the boundary conditions. Let us now discuss where the solutions we have obtained can be used. In [23], the processes of drilling wells in permafrost conditions are studied. This just corresponds to Stefan's problem about the freezing of a reservoir. As a result of mathematical modeling, the authors of this work obtain a nonlinear equation of such complexity that even with the current level of development of computer technology it is impossible to solve it. Subsequent simplifications made it possible to reduce the nonlinear equation to a system that consists of two linear homogeneous differential equations in two variables. The resulting solution turned out to be valid only in the case when the temperature regime of the well remains constant, which is obviously not true. We will demonstrate the use of our solution to this problem in the next article.

In [24], nonlinear elastic waves of the pendulum type were found in rock masses, which correspond to deformation-wave processes during the destruction of rocks. The pendulum type of elastic waves is described by Bessel-type formulas, as in our case. The theory of such waves has not yet been constructed. But the type of oscillations itself is very similar to the movement of moving boundaries, that is, it is close to the Stefan problem considered by us in this article for a finite cylinder.

The work [25] is purely theoretical and, as in our case, is devoted to the theory of the formation of microcracks in a rock mass. Stress calculation was carried out by the method of finite-discrete elements. In this case, the dependence of the voltage on the bias was non-linear. The conclusions proposed in the paper about the radial and axial components of the stress are in good agreement with our data obtained analytically.

The paper [26] also discusses nonlinear problems of soil and rock mechanics. These theories are based on the fact that volumetric and shear deformations depend only on shear stresses, as we put it in formulas (1) and (2).

Conclusion

In the process of drilling, as well as using hydraulic fracturing with polymer drilling fluids, microcracks are formed in the coal seam, through which methane flows. Our task is to construct a theoretical model of the development of these microcracks in order to give a way to extract methane from coal seams. We managed to solve this problem for the well by selecting the integral transformation. Our experimental and theoretical results fit into the model of macroscopic localization of plastic flow. The Bessel functions obtained in the equations in the well describe a periodic wave process. An analysis of the wave characteristics of such processes made it possible to measure their propagation velocity (~ 10^{-4} m/s), wavelength (~10^{-2} m) and establish that the dispersion relation for such waves has a quadratic character.

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