Розроблено спосіб оцінки навантаженості довільних перерізів колони насосних штанг з врахуванням фактичних умов їх експлуатації. Обґрунтовано основні принципи реалізації способу. Наведено приклади аналітичної та графічної інтерпретації функції зміни осьового навантаження в різних конструкціях колон насосних штанг. Встановлено можливість прогнозування довговічності елементів колони за відомими законами зміни осьових навантажень, що діють впродовж робочого циклу на заданій глибині

Ключові слова: колона насосних штанг, осьове навантаження, глибинна динамограма, модель колони насосних штанг

Разработан способ оценки нагруженности произвольных сечений колонны насосных штанг с учетом фактических условий их эксплуатации. Обоснованы основные принципы реализации способа. Приведены примеры аналитической и графической интерпретации функции изменения осевой нагрузки в различных конструкциях колонн насосных штанг. Установлена возможность прогнозирования долговечности элементов колонны по известным законам изменения осевых нагрузок, действующих в течение рабочего цикла на заданной глубине

Ключевые слова: колонна насосных штанг, осевая нагрузка, глубинная динамограма, модель колонны насосных штанг

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DEVELOPING A METHOD FOR THE ASSESSMENT OF AXIAL LOAD IN ARBITRARY CROSS-SECTIONS OF THE COLUMN OF PUMPING RODS

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1. Introduction

The boreholes in the petroleum industry of Ukraine mostly employ rod borehole pumping plants (RBPP). In the process of oil extraction with RBPP, a column of pumping rods (PR) is exposed to the action of system of static and dynamic forces. For accurate and objective evaluation of the stressed-strained state of the PR column, it is necessary to have reliable information about axial static and dynamic loads that act in its cross-sections at different depth. That is why the studies aimed at obtaining it are absolutely relevant.

2. Literature review and problem statement

PR column is a mechanical system that consists of a large number of sequentially interconnected rods. The complexity of static calculation of PR column is explained by the fact that, due to a large quantity of points of interaction with the column of pump-compressor pipes (PCP), a column of PR passes into a statically undefined system.

In order to calculate statically undefined rod systems, well-known methods are applied: force method, method of cross sections, a displacement method, finite element method and the combined method. The main shortcoming of calculating static loads on the PR column is their complexity and cumbersome procedure. Thus, in the course of static calculation with the introduction of main system, there is a necessity to perform calculations several times: on the effect of the assigned load and on the action of each unknown displacement in the direction of the imposed relations.

An alternative method for assessing the loading of PR column is modeling the dynamic processes, which typically comes down to compiling and solving the systems of differential-algebraic equations. Accurate solution to such systems whose number of equations matches the quantity of rods at present requires the existence of analytical dependencies, which could describe spatial deformations in the sections of a column. Complications of dynamic calculation arise when computing coefficients of canonical equations, their free members, as well as the integration constants. Along with this, article [1] explored dynamic behavior of rod systems taking into account the external force factors that are described by the multivalued (subdifferential) ratios. A boundary problem was stated with nonlinearities for friction in the form of variational and quasistationary inequalities. The algorithm of numerical realization for calculating rod columns of RBPP was proposed.

A problem on the propagation of elastic waves of impact character in a rod whose one end moves with acceleration by the given law, with another one loaded by weight and supported by spring, was considered in [2]. Propagation of elastic waves and development of deformations in the rod were determined using normal functions. Study of parameters of dynamic instability of PR column and corresponding vibration characteristics based on a comprehensive mathematical model was conducted in [3]. Determining the nature of influence of dynamic instability on the motion law of PR column in the directed borehole and numeric investigation into parameters of its operation continued in papers [4, 5].

Assessment of the magnitude of dynamic loads for the single and two-step PR columns was performed in [6]. By the results of theoretical studies, the ways were proposed to reduce dynamic loads and specific conditions were defined to prevent parametric resonance. Paper [7] is devoted to determining coefficient of damping fluctuations of PR column based on the dynamograms obtained in the course of experimental research. The impact was established of change in the amplitude and period of fluctuations of load over time on the attenuation coefficient along the entire length of the column.

Article [8] proposed a technique for constructing wellhead dynamogram by simulating the operating conditions of plunger. The implementation of this technique makes it possible to study the operation of pumping unit at different parameters of rods, conditions of their loading, motion frequency and stroke length of the pump rod. Paper [9] proposes realization of tools to analyze dynamograms on the level of borehole controllers of automated operation of downhole rod pumps. It was proposed to analyze not only wellhead and plunger dynamograms, but also to calculate deep dynamograms, to run spectral analysis of arrays of dynamograms and determine the stresses in rods. These works, however, do not take into account the peculiarities of interaction between PCP columns and PR columns in the bended sections of the borehole. Results of these studies are partially highlighted in [10].

In addition to the analytical methods described, when calculating especially complex systems, different numerical methods have been recently employed that are rapidly implemented by using automated computer systems.

As far as the level of RBPP loading is concerned, the basic method at present is its wellhead dynamometering. In order to obtain accurate and objective information on the work of deep equipment, it is appropriate to analyze its deep (plunger) dynamogram. In the 1990s, the Albert Engineering laboratory (USA) designed a deep dynamograph and conducted a series of experiments, as the results of which deep dynamograms were received for a few dozen boreholes [11].

However, it is well known that a wellhead dynamogram, obtained at the surface, is different from the plunger one. At a distance from the wellhead, with a gradual increase in the length of PR column, its weight, the forces of inertia and friction, caused by curvilinearity of the borehole, the resulting axial forces take the values different from each other. Receiving deep dynamograms requires the installation of additional sensors of force and displacement, as well as the existence of a data transfer channel to the surface. The implementation of such a system on industrial scale will lead to unnecessary cost increase in the downhole equipment.

3. The aim and tasks of the study

The aim of present study is to develop a method for evaluating the load in the arbitrary cross-sections of a pump rod column, considering actual operating conditions.

To achieve the set aim, the following tasks are to be solved:

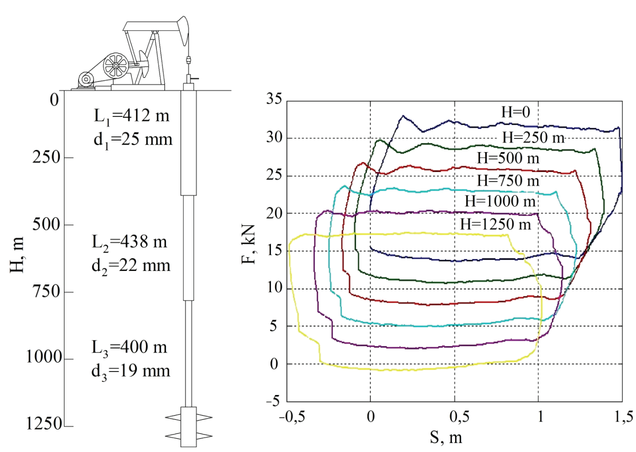
– to substantiate basic principles for the realization of procedure to determine loads in the arbitrary cross-sections of a PR column;

– to propose variants for the interpretation of function of change in the axial load in a PR column.

4. Substantiation of basic principles for the implementation of procedure for determining loads

When addressing a question on the transfer of information from the borehole to the surface, it is necessary to note that during construction of boreholes, as a mechanical communication channel, a column of drill pipes is widely used. Examples include remotely operated systems of such leading American companies as Sperry San, Sperry Research, Exploration Research. With regard to this, in the role of mechanical communication channel between the wellhead and the location of installing deep pumping equipment, which is a part of RBPP, it is advisable to use a PR column. Then, in order to obtain operational and objective evaluation of force loading in the arbitrary cross-sections of PR column, it is essential to have a wellhead dynamogram and a certain functional dependence between force parameters of the column's cross-sections. This can be a relationship between the resulting axial forces at the "top" and "bottom" of the column, respectively, mapped in the form of a special transmission characteristic – force transfer function.

According to the theory of automatic control [12], transmitting function is the function that describes transition process in the mechanical system and establishes relationship between its incoming and outgoing signal. Incoming and outgoing signal for a PR column are, accordingly, dynamograms at the "top" and "bottom" of the column derived by experimental or calculated way (Fig. 1) [9, 11].



a *b*

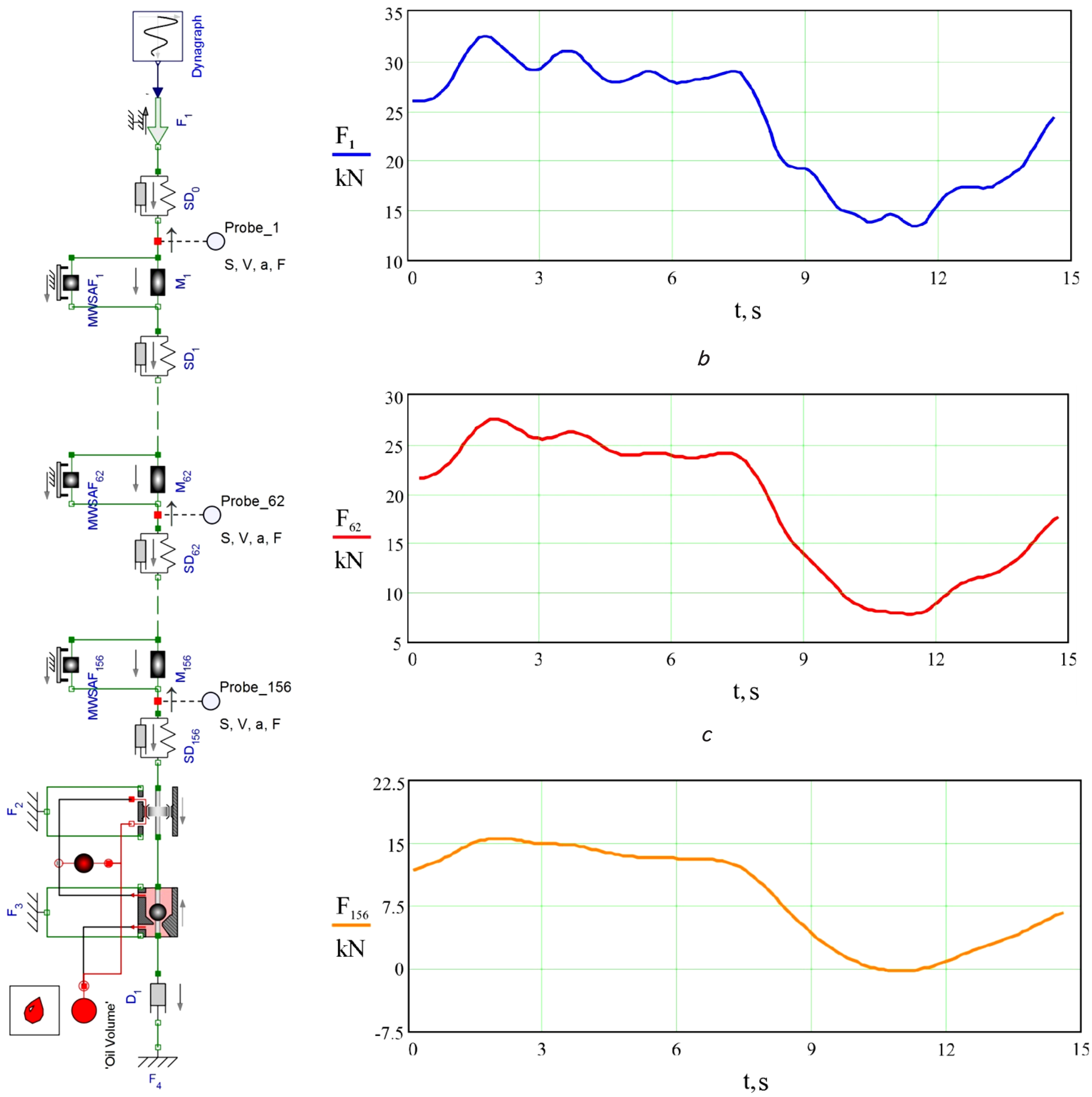
Fig. 1. Results of theoretical studies into the loading of PR column according to [9, 11]: *a* — assembly of the column; *b* — dynamograms obtained for the cross-sections of the column at interval 250 m

With regard to the aforementioned, in the MapleSim programming environment we created models of one-, two- and three-level columns of PR. In this case, we employed known parameters (Table 1) of configurations, operational modes of RBPP and the procedure for theoretical research, highlighted in [13]. For each of the column, four models were built. Their number is due to the existence of specific sections on wellhead dynamograms that require approximation when assigning the law of effort change in the point of hanging a PR column [7]. An example of one of the models is shown in Fig. 2. Each model is formed in a way that allows us to receive values of both kinematic and force parameters in the required cross-sections of the column.

Table 1

Arrangements of PR columns and parameters of operational modes of RBPP

No. of arrangement	Length and diameter of levels						Pump conditional diameter	Length of motion of the point of hanging the rods	Motion frequency of balancer head
	l_1, m	d_1, mm	l_2, m	d_2, mm	l_3, m	d_3, mm	mm	m	min^{-1}
1	1000	22	–	–	–	–	32	3	5
2	464	22	736	19	–	–	32	3	5
3	412	25	438	22	400	19	44	2,1	4



a *d*

Fig. 2. Results of the simulation in the MapleSim programming environment: *a* — model of a three-level PR column; *b* — sweep of model dynamogram at the wellhead of borehole; *c* — sweep of model dynamogram at depth 500 m; *d* — sweep of model dynamogram at depth 1250 m

By numerical examination of the created models, we obtained dependences of change in axial forces over time for different cross-sections of the column. In order to compare the results obtained to the results given in [9, 11] (Fig. 1), indicated dependences are represented in the form of a sweep of the wellhead dynamogram and dynamograms for the cross-sections at depth 500 and 1250 meters (Fig 2, *b–d*). As anticipated, the amplitude of change and maximum axial strength value in the transverse cross-sections of PR column near the wellhead are larger than the corresponding parameters in the transverse cross-sections, located at depth.

Results of examining a change in the loads lengthwise the RP columns indicate that for conditionally vertical boreholes, dynamogram character depends on the operation mode of RBPP, arrangement of columns and the forces of their interaction with NCP.

5. Analytical and graphical interpretation of the function of change in the axial load in the PR column

In order to establish a force transfer function form the laws of change in axial forces for the calculated cross-sections (1, 2, 3,..., n) whose position is determined by the longitudinal coordinate x, we defined maximum values of forces F_{1max}, F_{2max}, F_{3max},...., F_{nmax}. For the analytical interpretation of the function of change in the axial forces lengthwise the PR column, in the Microsoft Excel environment we approximated the data obtained in the form of polynomial equations of sixth power for each of the examined variants:

– for arrangement No. 1

$$F(x)=2\cdot10^{-11}x^4-4\cdot10^{-8}x^3+ \\ +2\cdot10^{-5}x^2-0{,}0255x+32{,}5; \qquad (1)$$

– for arrangement No. 2

$$F(x)=4\cdot10^{-16}x^6-1\cdot10^{-12}x^5+2\cdot10^{-9}x^4- \\ -1\cdot10^{-6}x^3+0{,}0003x^2-0{,}0494x+47{,}4; \qquad (2)$$

– for arrangement No. 3

$$F(x)=-4\cdot10^{-14}x^5+1\cdot10^{-10}x^4 1\cdot10^{-7}x^3+ \\ +5\cdot10^{-5}x^2-0{,}0213x+32{,}7. \qquad (3)$$

For the examined arrangements, dependences that illustrate a change in the axial force lengthwise the PR column are given in Fig 3.

In some cases, for convenient and effective research into dynamics of long-dimensional mechanical systems, it is expedient to operate with dimensionless transfer functions. If we know an input signal, such functions make it possible to determine appropriate parameters in the required point of the system. The value of transfer function for arbitrary n-th cross-section of PR column, located at certain depth, was defined according to the following ratio:

$$w_{Fn}=\frac{F_{1max}}{F_{nmax}}, \qquad (4)$$

where F_{1max} is the maximum force value in the cross-section of wellhead rod; F_{nmax} is the maximum force value in the n-th cross-section of the column.

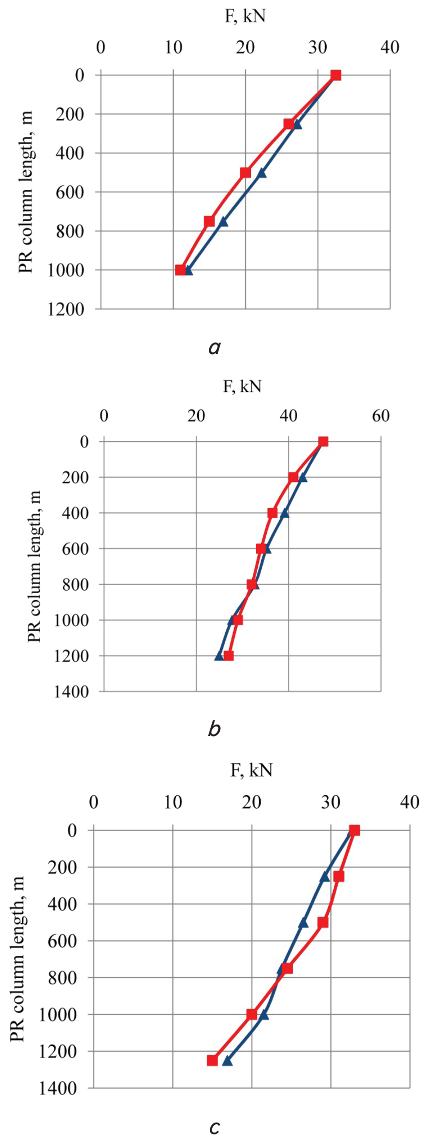


Fig. 3. Charts of change in the maximum axial loads along the length of PR columns: *a* — arrangement No. 1; *b* — arrangement No. 2; in — arrangement No. 3; —▲— — according to dynamograms (Fig. 1 [8]); —■— — by results of the simulation

Fig. 4 shows graphical dependences of the received transfer functions on the length of PR columns. To obtain an analytical expression for the calculation of transfer functions, we carried approximation of respective curves in the form of polynomial equations of sixth power.

According to the results of approximation, the following empirical dependences were established for the numerical calculation of transfer functions of the PR columns:

– for arrangement No. 1, δ=250 m,

$$w_F(x)=4\cdot10^{-13}x^4-2\cdot10^{-10}x^3+ \\ +9\cdot10^{-7}x^2+0{,}0008x+1; \qquad (5)$$

– for arrangement No. 2, δ=200 m,

$$w_F(x)=-2\cdot10^{-18}x^6+7\cdot10^{-15}x^5-8\cdot10^{-12}x^4+ \\ 3\cdot10^{-9}x^3-7\cdot10^{-7}x^2+0{,}0009x+1; \qquad (6)$$

– for arrangement No. 3, δ=250 m,

$$w_F(x) = 3\cdot 10^{-15}x^5 - 1\cdot 10^{-11}x^4 + 1\cdot 10^{-8}x^3 - 5\cdot 10^{-6}x^2 + 0{,}0009x + 1. \quad (7)$$

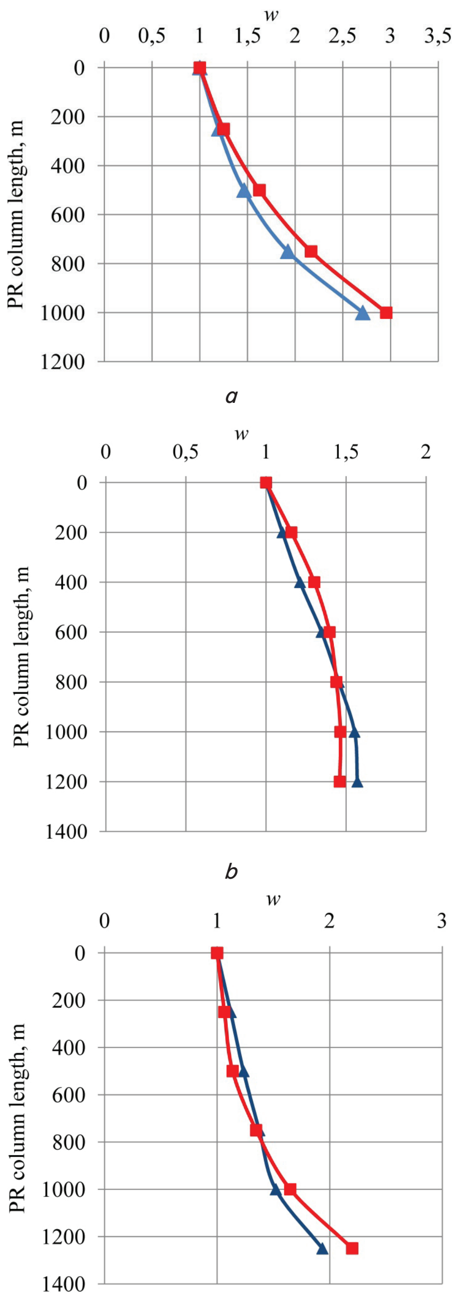


Fig. 4. Charts of transfer functions of the PR columns: *a* — arrangement No. 1; *b* — arrangement No. 2; *c* — arrangement No. 3; —▲— — according to dynamograms (Fig. 1 [8]); —■— — by results of the simulation

6. Discussion of results of examining a change in the axial load in a PR column using the method proposed

Results of theoretical studies indicate that there is a general tendency of increase in the transfer functions in the transition from the upper rods of PR columns to the lower ones. However, this growth is non-monotonous and indicates that the value of axial load is significantly affected by the interaction between a PR column and the PCP column.

The proof of it is the results of conducted analysis on the failures in PR columns at the NGVU "Dolinanaftogaz" of PAT "Ukrnafta". For example, in the borehole No. 820, over two years we registered 15 failures, 14 of which are caused by the break-up of couplings. When matching the depth of PR column break-up with the profile of borehole, there were discovered two conditional zones of the occurrence of failures: zone I – in the middle, zone II – in the bottom part of PR column (Fig. 5). In the indicated areas, the effort that pushes PR column closer to PCP is considerably larger than that for the conditionally vertical boreholes.

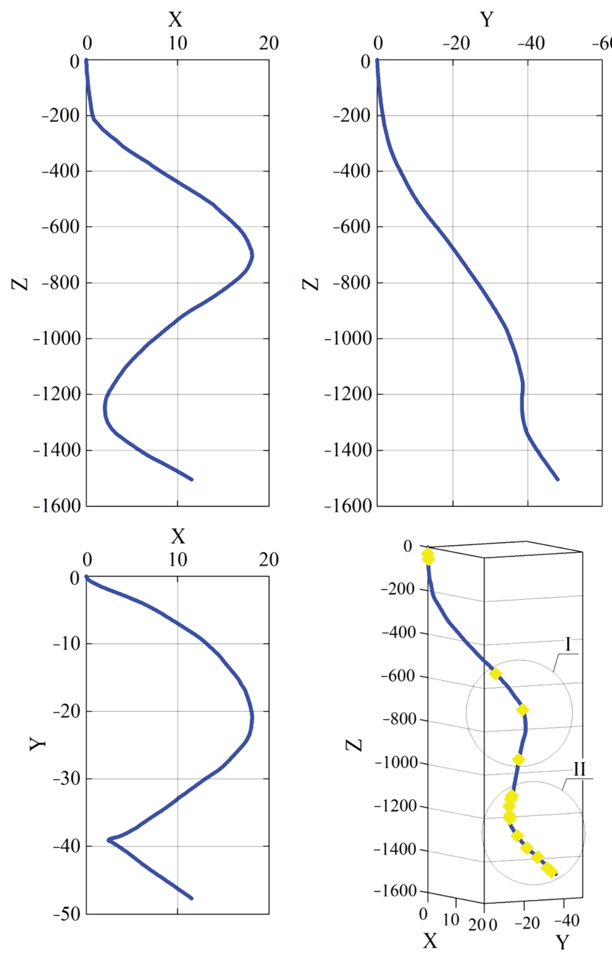


Fig. 5. Profile of borehole No. 820 in the descending interval of a PR column

That is why, in order to maximally consider the operating conditions of deep RBPP equipment, at the stages of design or correction of the design of a PR column, it is necessary to conduct detailed analysis of the profile of the borehole in the descending interval of PR column. For the sections with a large intensity of curvilinearity, it is necessary to further investigate the interaction forces between PR and PCP using the aforementioned [10] or other known methods [14]. Introducing their values into the model under development will contribute to maximal convergence of results of the simulation to the real picture of loading the rods in the arbitrary cross-sections of the column.

Availability of the laws of change in the axial load over the cycle of RBPP operation, obtained for arbitrary cross-sections, allows us to determine stresses in PR for specific sections of the column. This also provides for the possibility to assess their durability or residual resource.

7. Conclusions

Employing the results of theoretical studies, we propose a method for evaluating the load in the arbitrary cross-sections of the column of pumping rods with regard to their actual operation conditions. For this purpose:

1) simulation models of PR columns are constructed that take into account their design features, parameters of RBPP operating modes, peculiarities of interaction between the columns of PCP and PR and the laws of effort change in the point of their hanging;

2) simulation results obtained for different cross-sections of a PR column are represented as functions of change in the axial load, allowing us to track the magnitude of its change depending on the depth of a borehole.

Maximum consideration of the operating conditions of RBPP deep equipment is achieved by running a detailed analysis of the profile of the borehole and determining the efforts of interaction between PR and NCP in the sections with a large intensity of curvilinearity. The operations specified might be performed at the stages of design or correction of the design of a PR column.

Practical significance of these calculations consists in the possibility to analyze the stressed-strained state and durability of elements in a PR column by the known laws of change in the axial loads that act during operation cycle at the set depth.

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