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STUDY OF THE DYNAMICS OF ASSOCIATED DRILL STRINGS INTERACTING WITH THE WELL WALL



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The depth of exploration and production wells during the development of oil and gas fields can exceed 5-10 km, and the insufficient strength and reliability of the drill string often limits the possibility of further increasing labor productivity. In addition, accidents at wells lead to significant material costs. Therefore, the design and operation of drill strings, as well as the implementation of work to eliminate complications during drilling, should be carried out on the basis of a science-based approach, taking into account the latest advances in the field of drill string dynamics and technologies related to work to eliminate stuck problems.

Unsteady vibrations of inhomogeneous distributed systems is a very complex problem in the mechanics of a deformable solid and the theory of vibrations. In connection with the rapid development of the extractive industries, solving this problem is of particular importance. This is due to ensuring the strength of drill string structures with increasing power and speed of drilling units and mechanisms. The study of the problem revealed a number of little-studied problems, which include issues of nonlinear interaction of the column with the surrounding soil, accompanied by various types of complications (sticking, pipe ruptures, etc.), wave and oscillatory processes in the elements of the drilling dynamic system (DDS), finding the boundaries of the interaction areas of the column with the walls of the well using low-cost techniques.

The purpose of the work is theoretical research of wave and oscillatory processes in the pipes of the drilling assembly and the dynamics of associated drill strings interacting with the well wall.

In this work, a homogeneous rod was used as a drill string model. The drill string consists of a drill pipe string (DPC) and a bottom drill string assembly (BDSA), which includes a bit, a downhole motor, wellbore forming elements: calibrators, centralizers, sections of drill collars (DC), the main purpose of which is to creating an axial load on the bit. The DPC consists of sections of drill pipes that are identical in their characteristics (type, outer diameter, wall thickness, joints used, etc.). Therefore, in general, the drill string is a heterogeneous structure.

KEY WORDS: *field, drill string, well, calibrator, centralizer, rod, increase drilling efficiency.*

ҰҢҒЫ ҚАБЫРҒАСЫМЕН ӨЗАРА ӘРЕКЕТТЕСЕТІН ТҮЙІНДЕС БҰРҒЫЛАУ ҚҰБЫРЛАРЫНЫҢ ДИНАМИКАСЫН ЗЕРТТЕУ

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Мұнай және газ кен орындарын игеру кезінде барлау және пайдаланылатын ұңғымалардың тереңдігі 5-10 км-ден асуы мүмкін, ал бұрғылау құбырлары бағанының беріктігі мен сенімділігінің жеткіліксіздігі көбінесе еңбек өнімділігін одан әрі арттыру мүмкіндігін шектейді. Сонымен қатар, ұңғымалардағы апаттар айтарлықтай материалдық шығындарға әкеледі. Сондықтан Бұрғылау колонналарын жобалау және пайдалану, сондай-ақ бұрғылау кезіндегі асқынуларды жою жөніндегі жұмыстарды жүргізу Бұрғылау колонналарының динамикасы мен прихваттарды жою жөніндегі жұмыстарды жүргізуге қатысты технологиялар саласындағы соңғы жетістіктерді ескере отырып, ғылыми негізделген тәсіл негізінде жүзеге асырылуы тиіс.

Біртекті емес таратылған жүйелердің тұрақсыз тербелістері Деформацияланатын қатты механика мен тербеліс теориясының өте күрделі мәселесі болып табылады. Өндіруші салалардың қарқынды дамуына байланысты бұл мәселені шешу ерекше маңызға ие болады. Бұл бұрғылау қондырғылары мен механизмдерінің қуаты мен жылдамдығы артқан кезде бұрғылау бағаналарының конструкцияларының беріктігін қамтамасыз етуге байланысты. Мәселені зерделеу бірқатар аз зерттелген міндеттерді анықтады, оларға әртүрлі асқынулармен бірге жүретін бағананың қоршаған топырақпен сызықтық емес өзара әрекеттесуі (ұстамалар, құбырлардың үзілуі және т.б.), бұрғылау динамикалық жүйесінің элементтеріндегі толқындық және тербелмелі процестер, бағанның ұңғыманың қабырғаларымен өзара әрекеттесу учаскелерінің шекараларын табу жатады. арзан әдістерді қолдану.

Жұмыстың мақсаты-ұңғыманың қабырғасымен әрекеттесетін бұрғылау қондырғысының құбырларындағы толқындық және тербелмелі процестерді және конъюгацияланған бұрғылау бағандарының динамикасын теориялық зерттеу.

Жұмыста бұрғылау бағанының моделі ретінде біртекті өзек қолданылады. Бұрғылау бағанасы бұрғылау құбырларының бағанасынан (БҚБ) және бұрғылау бағанының төменгі бөлігінің (ББТБ) орналасуынан тұрады, оған қашау, кенжар қозғалтқышы, ұңғыма оқпанын қалыптастыру элементтері кіреді: калибраторлар, орталықтандырғыштар, негізгі мақсаты қашауға осьтік жүктеме жасау болып табылатын салмақты бұрғылау құбырларының секциялары (БҚС). БҚБ өзінің сипаттамалары бойынша бірдей бұрғылау құбырларының секцияларынан тұрады (түрі, сыртқы диаметрі, қабырға қалыңдығы, қолданылатын құлыптар және т.б.). Сондықтан, жалпы жағдайда бұрғылау бағанасы гетерогенді құрылым болып табылады.

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ИССЛЕДОВАНИЕ ДИНАМИКИ СОПРЯЖЕННЫХ БУРИЛЬНЫХ КОЛОНН, ВЗАИМОДЕЙСТВУЮЩИХ СО СТЕНКОЙ СКВАЖИНЫ

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Глубина разведочных и эксплуатируемых скважин при разработках нефтяных и газовых месторождений может превышать 5-10 км, а недостаточная прочность и надежность колонны бурильных труб часто ограничивают возможность дальнейшего повышения производительности труда. Кроме того, аварии на скважинах приводят к значительным материальным затратам. Поэтому проектирование и эксплуатация бурильных колонн, а также проведение работ по ликвидации осложнений при бурении должно осуществляться на основе научно-обоснованного подхода с учетом последних достижений в области динамики бурильных колонн и технологий, касающихся проведения работ по ликвидации прихватов.

Нестационарные колебания неоднородных распределенных систем является весьма сложной проблемой механики деформируемого твердого тела и теории колебаний. В связи с бурным развитием добывающих отраслей промышленности решение этой проблемы приобретает особое значение. Это связано с обеспечением прочности конструкций бурильных колонн при возрастающей мощности и скорости бурильных агрегатов и механизмов. Изучение проблемы выявило ряд малоизученных задач, к которым относятся вопросы нелинейного взаимодействия колонны с окружающим грунтом, сопровождающего различными видами осложнений (прихваты, разрывы труб и др.), волновые и колебательные процессы в элементах бурильной динамической системы (БДС), нахождение границ участков взаимодействия колонны со стенками скважины с использованием малозатратных методик.

Цель работы: проведение теоретических исследований волновых и колебательных процессов в трубах бурильной компоновки и динамики сопряженных бурильных колонн, взаимодействующих со стенкой скважины.

В работе использованы в качестве модели бурильной колонны однородный стержень. Бурильная колонна состоит из колонны бурильных труб (КБТ) и компоновки нижней части бурильной колонны (КНБК), включающей в себя долото, забойный двигатель, элементы формирования ствола скважины: калибраторы, центраторы, секции утяжеленных бурильных труб (УБТ), основное назначение которых заключается в создании осевой нагрузки на долото. КБТ состоит из секций бурильных труб, идентичных по своим характеристикам (типу, наружному диаметру, толщине стенки, используемым замкам и т.д.). Поэтому в общем случае бурильная колонна представляет собой неоднородную конструкцию.

КЛЮЧЕВЫЕ СЛОВА: *месторождение, бурильная колонна, скважина, калибратор, центратор, стержень, повышения эффективности бурения.*

Introduction. The depletion of oil and gas fields being developed in the world leads to the need to drill new wells. Expenditures associated with oil exploration and drilling in the United States in 1990 amounted to about $11 billion. From the extraction of minerals from large natural reservoirs, we gradually have to move to smaller reservoirs, which also requires more frequent and technologically advanced drilling of new wells [1,2]. As a result, modern oil and gas drilling is an economically important and technologically complex process. The installation for drilling deep wells is comparable in scale to a factory, and the cost of the equipment is very high. Economic factors make the task of increasing drilling efficiency, studying emerging difficulties and finding ways to eliminate them an important object of both practical and theoretical consideration. The value of studying the drilling process [3], together with the complexity and versatility of its inherent physical phenomena, leads to a large number of scientific studies devoted to this issue. One of the most studied and, however, still not fully resolved problems in deep drilling is the problem of unwanted vibrations of the drill string.

Despite the use of electronic equipment, in most cases drilling remains primarily a mechanical process. The strength and static stability of the structure are necessarily studied when designing an installation, however, it is almost impossible to predict in advance and completely the dynamic behavior of the system due to the large number of operating factors, which can only be taken into account approximately[4]. Extensive literature is devoted to torsional vibrations of the drill string.

Research. In one of the early works [5], the column is considered as a torsional pendulum with one degree of freedom, and the dependence of the moment of resistance to rotation at the bottom point on the angular velocity is considered to decrease exponentially. In [6], a theory of oscillations with periods of slipping and stagnation was constructed under the assumption of a jump-like characteristic of friction in the "bit-bottomhole" pair. The falling friction characteristics at the point of contact of the bit with the rock and on the walls of the well are accepted in works [7,8]. They analyzed the areas of stability of the mode of uniform rotation of the column by decomposing elastic torsional vibrations into modes, which makes it possible to develop practical recommendations for eliminating unwanted vibrations. This takes into account the falling characteristic of the engine torque, which plays a stabilizing role. Torsional vibrations of the drill string with periods of slipping and stagnation and with an exponential characteristic of friction between the bit and the rock are also considered in [9].

We study the longitudinal displacements of an elastic rod of length L, modelling a drill string in a vertical well, and its stresses arising under the action of a tensile axial static load, dynamic effects at the end and its own weight, uniformly distributed along the length of the string. It is believed that the outer surface of the rod has local areas where interaction with the rock occurs according to the law of dry friction. The resistance forces F_{mp} arising in the contact zone depend on the external and internal diameters of the column (*D, d*), the size of the sticking point (l_2), the lateral resistance (*k*), the specific gravity of the rock (*γ*), the coefficient of friction of the rock on the pipe (*f*), as well as from the depth of the section (*x*) relative to the upper limit of the sticking (l_1).

Let us assume that at the end of the lower part, represented by weighted pipes, there is an additional mass (bit) [10]. In this case, the mating of pipes of different sections occurs at a depth of 900 m. The outer diameter of the pipes of the upper part, as before, is 140 mm, and the lower part is 200 mm; internal (for all pipes) – 120mm. The mass of the bit at the end of the drill collar is accepted *m=100kg*.

Expressions for the potential energy of longitudinal deformation of an elastic rod, kinetic energy and the potential of external forces (gravity, friction and axial load at the end and in the section xi of the inner surface of the column) have the form

$$U = \frac{1}{2}\int_0^L EF\left(\frac{\partial u}{\partial x}\right)^2 dx$$

$$T = \frac{1}{2}\int_0^L \rho F\left(\frac{\partial u}{\partial t}\right)^2 dx \tag{1}$$

$$\Pi = \int_0^L \rho gFxudx - \int_{l_1}^{l_1+l_2} F_{mp}(x)udx - Nu\Big|_0^L$$

where, E, ρ, F – modulus of elasticity, material density and cross-sectional area of the pipe; (l_1, l_2) – pipe section with frictional forces in contact with the rock; *N* – axial load at the end, which is either a static tensile axial load *N=const* or dynamic load *N=N(t)* at the end; *u* – longitudinal movement of the rod.

The equation for longitudinal vibrations of a column with a longitudinal axis x is described by the equation

$$-\frac{\partial}{\partial x}\left(EF\frac{\partial u}{\partial x}\right)+\rho F\frac{\partial^2 u}{\partial x^2}=q(x,t) \qquad (2)$$

where, q(x,t) – total static and dynamic load, including the axial load at the end of the column, the force in the contact zone, as well as the force of gravity distributed along the length of the column. According to the hypothesis of plane sections, any points lying in a plane perpendicular to the axis of the rod have the same displacements $u_1=u(_x)$. All components of the stress and strain tensors, except σ_{11} and ε_{11}, are considered negligible.

The following boundary conditions were accepted:

an axial force is applied at the upper end, i.e.

$$x=0: \quad EF\frac{\partial u}{\partial x}=N(t)\,, \qquad (3)$$

the lower one carries concentrated mass *m*

$$x=L: \quad m\frac{\partial^2 u}{\partial t^2}=-EF\frac{\partial u}{\partial x}=0\,, \qquad (4)$$

on the contact surface in the area $(l_1;l_1+l_2.)$ there is a friction force, depending on the location of the section *x* relative to the upper boundary of the stick l_1, the coefficient of friction of the pipe with the rock *f*, the lateral resistance *k*, the specific gravity of the rock *γ*, the outer diameter of the column *D* and the direction section speed *ú*:

$$l_1<x<l_1+l_2: \quad EF\frac{\partial u}{\partial x}=-F_{mp}\,sign(\dot{u}\,(x))$$

$$\text{where} \quad F_{mp}=\frac{4D\gamma_n fk}{D^2-d^2}x\,. \qquad (5)$$

Under static load –

$$l_1<x<l_1+l_2: \quad EF\frac{\partial u}{\partial x}=-F_{mp} \qquad (6)$$

The initial conditions are homogeneous, i.e.

$$\text{at } t=0: \quad u0=0, \quad \acute{u}_0=0. \qquad (7)$$

Solution of the assigned dynamic problem of vibrations and the stress-strain state of a column having a section with friction (sticking) under the influence of applied static and dynamic loads (3-6), initial conditions (7) analytically - by methods of mathematical physics - is quite difficult. Therefore, to solve it, the numerical finite element method was used.

The elastic rod used to model the drill string was discretized using rod elements with a linear approximation of the displacement field inside the element [11].

A column with a length of *L=1000m*, an outer diameter of *140mm* and a wall thickness of *10mm* is being considered. In this case, the cross-sectional area is $F=40cm^2$. At $E=2.1e^5$ *MPa*, $\rho=7.8e^3kg/m^3$, the speed of propagation of longitudinal waves will be $c=(E/\rho)^{1/2}=5000$ *m/sec*, and the main period of longitudinal oscillations *T=0.4s*. The last two parameters (wave speed and oscillation period) appear when considering dynamic processes in the column.

As a result, a finite element discretization of problem (2) with boundary conditions (3-5) results in a system of differential equations of general form

$$\mathbf{M}\ddot{u} + \mathbf{K}u = \mathbf{P}(t) \tag{8}$$

where **M** and **K** – column mass and stiffness matrices; **P**(t) – specified dynamic influence.

System (8) with initial conditions (7) is solved by the Newmark method [12]. Based on the detected displacements, deformations and stresses in the studied sections of the column are determined depending on time.

Let us consider the dynamics of a column when a single pulse is applied to the end of the column

$$P(t) = \begin{cases} A & 0 \le t \le \tau \\ 0 & t \succ \tau \end{cases} \text{at} \tag{9}$$

The dynamics of changes in displacements and stresses in the body of a column stuck in a section of 500-600 m under the influence of a short-term dynamic load at the end (9) with a duration of $\tau=0,1s$ and an amplitude of $A = 1.1$ MPa is shown in *Fig. 1*

The accompanying high-frequency stress fluctuations in the section where pipes of different diameters are connected are associated with its close location to the end of the pipe and the superposition of direct and reflected waves. In general, it is clear that the maximum stresses in the section under study are comparable to the stresses in the upper part of the column. Comparing these results with the stresses in the lower part of a homogeneous pipe under the same influence, where the solid line is practically on the zero line, we can conclude that there is a significant increase in stresses at the junctions of pipes of different diameters.

In *Fig. 2*, the results were obtained under exposure with a period of $T = 0.4s$ and a pulse duration of $\tau=0.2s$. This case, unlike the results in *Fig. 2*, is no longer purely "resonant", because the geometric parameters of the column have changed, and, accordingly, its frequency and period. Yet, an increase in the amplitude of vibrations and stresses is observed, not only in the sticking area, but also at the junction of pipes of different diameters.

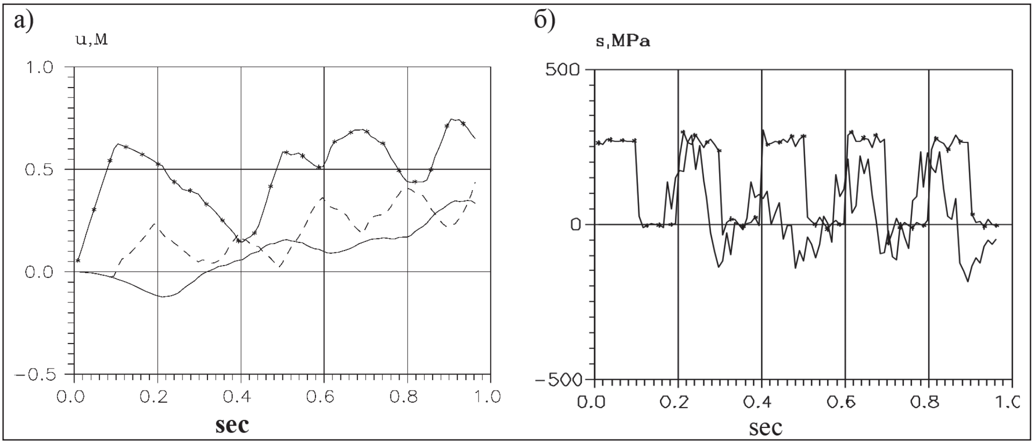

Figure 1 – **Changes in displacements (a) and stresses (b) in sections of a heterogeneous stuck column under repeated pulse action at the end with amplitude A = 1.1 MN, duration τ=0,1s and period T = 0.2s: —x—x— upper; ——— - upper part of the drill collar; - - - - - upper sticking limit (500m)**

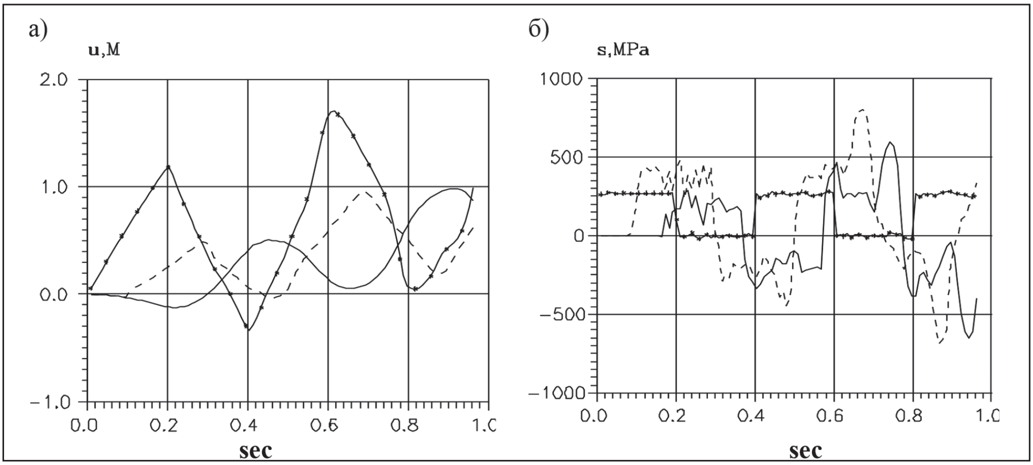

Figure 2 – **Changes in displacements (a) and stresses (b) in sections of a heterogeneous stuck column under repeated pulse action at the end with amplitude A = 1.1 MN, duration** ***τ*****=0,2s and period T = 0.4 s —x—x—- upper; ——— - upper part of the drill collar; - - - - - upper sticking limit (500m)**

The change in stress is accompanied by high-frequency harmonics associated, as in the previous example, with the reflection of waves from the boundaries of the inhomogeneity of the column structure.

Figure 3 shows the displacements and changes in the stress state in sections of a non-uniform column under low-frequency exposure with a period T=0.6s and pulse duration *τ*=0.3s.

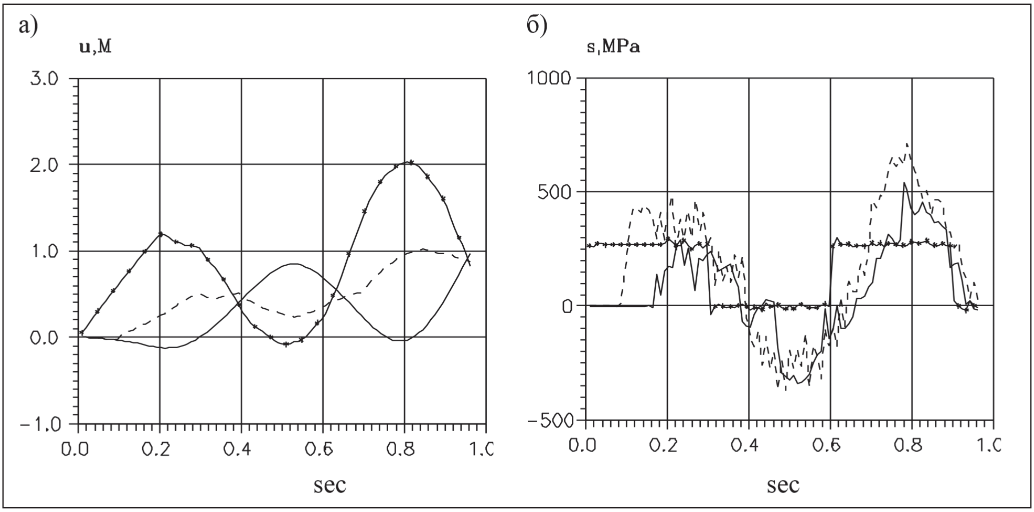

Figure 3 – **Changes in displacements (a) and stresses (b) in sections of a heterogeneous stuck column under repeated pulse action with amplitude A = 1.1 MN, pulse duration** ***τ*****=0,3s and period T = 0.6s: —x—x—- upper; ——— - upper part of the drill collar; - - - - - upper sticking limit (500m)**

Research shows that all three types of oscillations usually occur simultaneously, and therefore joint oscillations should be considered related. There are different points of view on the mechanisms of energy transfer from one type of vibration to another; a large number of works are devoted to the study of precisely coupled vibrations of the drill string. Thus, the reason for the occurrence of transverse vibrations is the instability of rotation that occurs in the VHA: the centrifugal force leads to an increase in the bending of the column, and even a slight bend of the well or an imbalance can greatly enhance the effect. The reason for the development of torsional vibrations is usually considered a decreasing characteristic of the moment of resistance to cutting on the bit, but most researchers agree that the mechanism for the occurrence of such vibrations includes the development of accompanying longitudinal vibrations [13]. The nonlinear nature of the interaction between the bit and the rock determines the relationship between these vibration modes.

Comparing the results in *Fig. 1* and *Fig. 3*, one can note a characteristic resonance increase in the amplitudes of displacements and stresses in the sections of the column, which is apparently associated with an increase in the period of natural oscillations of the inhomogeneous structure of the drill string compared to the homogeneous one. In this case, the stresses both in the sections of the column located in the stuck zone and at the boundary of the connection of various pipes exceed the tensile strength, which can cause damage to the column in these places.

Conclusions. Dynamic exposure to multiple pulses with a period close to or equal to the period of longitudinal vibrations of the column leads to an unlimited increase in stress in the stuck zone, which will lead to the destruction of the column.

Under low-frequency exposure, stresses in column sections do not exceed permissible values. However, repeated replacement of tensile stresses with compressive stresses in the stuck area can lead to fatigue damage to the column.

When a low-frequency pulse is applied to a stuck string consisting of mating drill pipes, not only the sections in the stuck zone, but also the areas where different pipes are connected are dangerous from the point of view of exceeding the tensile strength. For such a heterogeneous structure, high-frequency exposure with an amplitude not exceeding half the permissible load on the column is also more effective.

Thus, the studies have shown that the optimal selection of parameters for static and dynamic (pulse) effects on a stuck string can lead to directed movement of the string out of the well without destruction. In this case, the correct choice of loads depends on the size of the clamp. However, there are methods for determining only the upper limit of sticking, based on instrumental measurements of column deformation under static loading. There are no methods for determining the lower limit of sticking.

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