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CALCULATION OF DISTANCE BETWEEN ELASTIC-RIGID CENTRALIZERS OF CASING

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РОЗРАХУНОК ВІДДАЛІ МІЖ ПРУЖНО-ЖОРСТКИМИ ЦЕНТРАТОРАМИ ОБСАДНОЇ КОЛОНИ

Purpose. Formulation and solution to the problem of rational centering of the casing under the complex configuration of well axis using elastic-rigid centralizers.

Methodology. The model of the "casing-well" system is under consideration. In the simulation system, the column in the hole is loaded by two sets of forces: the forces of gravity, distributed along the axis of the pipe and pressure forces caused by the complex configuration of the well axis and distributed between the centering devices. The influence of structural peculiarities of the cyclically symmetric "bow" type centralizers on their rigidity and toughness characteristics has been taken into account. The solution of the problem will be considered found when the allowable minimum value of a gap in the "casing-well-wall" system is provided.

Findings. The dependencies to determine the distance between the centralizers and allowable gap have been determined on the basis of the solution of the problem of rod bending on the elastic-rigid supports. With the increase in zenith angle due to increased transverse component of gravity, the distance between centralizers reduces. Moreover, for small zenith angles it is even smaller, due to greater downforce. For large zenith angle as well as for large pressing forces, their influence on the distance between the centering devices is offset due to activation of the stop. In particular, it was determined that the stop of a centralizer provided it has sufficient strength can guarantee the required gap at considerable loads on the column. The results of the research have been approved by the engineering calculations for specific sizes of casing and well.

Originality. New dependencies to calculate the distance between the elastic-rigid centralizers used in casing the well taking into consideration groups of factors that determine the wellbore profile and centralizer specifications have been established.

Practical value. The obtained results provide for optimizing the exact number and intervals of equipping the casing with centering devices and thereby avoid the formation of dead zones in the annulus. This will give the opportunity to achieve high-quality cement job and make casing of the well of any configuration reliable and time-proof.

Keywords: *elastic-rigid centralizer, casing, gap, rational centering*

Introduction. The casing of oil and gas wells is one of the most important stages in their construction. The quality of plugging operations influences the performance of oil and gas production tasks by the well. When constructing directional and horizontal wells complications associated with poor cement job of casing strings may arise. Despite purely industrial problems (inter-reservoir cross flows, mud springs, intercolumnar pressures etc.) such complications may lead to severe environmental and financial consequences. The eccentric placement of the casing in the wellbore is the main reason for the complications in the process of cementing. In the narrow gaps between casing and borehole wall washing fluid is not replaced by cementing slurry, resulting in the formation of a zone of unilateral cementation. The process of formation of such zones is affected by the quality of the preparation of the wellbore for cementing, casing accessories, the number, and characteristics of the centering devices and intervals between their installation, the quality of cement slurry and other factors.

Despite the wide range of engineering solutions aimed at improving the reliability of well casing, the problem of centering the casing today remains relevant to the oil and gas industry, particularly in connection with the increase in volumes of directional and horizontal drilling. Reasonable equipping of the casing with a centering device is intended to contribute to its equidistance from the walls of the well and thus should not prevent the descent of the pipes to the prescribed depth. Thus, the quality of cementing the annulus will improve, which will ensure the efficient architecture of the wellbore.

Various types of centering devices are used to center a casing in an open hole. When drilling vertical and directional wells cyclically symmetric "bow" type centralizers [1] are most widely used. A number of recommendations are given in literary sources and in current guidance documents for application of balloon-type centralizer or using other construction. There is a method for calculating casing string for directional drilling presented in [2]. [3] describes the distance between the centralizers from the condition of the allowable arrow of curve for casing, [4] – discrete values of the distance between the centralizers, depending on the diameter of the string, [5] – centering of the with a hydromechanical module, [6] – the distance between the centralizers with the expectation of curve of casing pipes, zenith angle values and rigidity of casing pipes.

An inadequate rationale for the definition of location intervals and a number of centering devices, the mismatch between their elastic characteristics and the real load cause complications in the process of running casing into the well and have a negative influence on the quality of cementing. This can also lead to the overuse of centering devices in one interval and their insufficient number in other intervals.

This study **aims at** formulation and solution to the problem of rational centering of the casing under the complex configuration of a well axis using elastic-rigid centralizers.

To solve the problem we need to find the distance between the centralizers so that the smallest gap in the "casing-well" system exceeded the allowable minimum value necessary for high-quality cementing.

Statement of the problem. Let the casing be equipped with the spring centralizers with a nonlinear characteristic of radial rigidity. Now let us consider possible options for the location of column section in a well (Fig. 1).

Hereinafter let us adopt the following definitions and symbols: r_w is a well radius; r_{cnt} is a radius of a centralizer in an non-deformed state; r_{csn} a casing radius (in some cases we should keep in mind that $r_{csn} = r_{clr}$ is a collar radius); δ_{max} is the biggest (even gap); δ_0 is the tiniest (in a circle) gap between a casing and a well when a centralizer touches the wall; δ is the tiniest (in a circle) gap between the loaded column and the well; y is column axis movement relative to the well axis in the direction of the axis y (positive upwards) after selecting play $r_w - r_{cnt}$.

A column in the well is loaded by two systems of forces: forces of its own weight, distributed along the axis of the pipe and pressure forces caused by a complex configuration of the well axis and distributed along centralizers. Under the influence of these forces lateral movement of the column arises, which consists of displacements caused by the deformation of the centralizers and the elastic displacement of the axis of the pipe pertaining to centralizers. Such movements lead to gap δ narrowing. Fig. 1, *c* features the worst situation when the displacements caused by pressure forces and dead load have the same direction (in this case downward). The walls of the well by assumption are considered to be absolutely rigid.

The problem of effective centering of the casing is to find the distance between the centralizers so that the smallest gap in the "casing-well" system exceeded the allowable minimum value necessary for high-quality cementing

$$\min \delta \geq [\delta]. \quad (1)$$

To evaluate the dependence of δ on casing load let us consider a model problem.

Suppose that on some spudded interval the orientation and location of the borehole axis vary slightly. Assume that on this very interval they expect to install several centralizers. Then gravity and pressure forces can be considered as uniformly distributed, and consider the periodic problem of bending of infinitely long columns, placed on an elastic-rigid supports (Fig. 2). The corresponding diagram for the calculation is shown in Fig. 3.

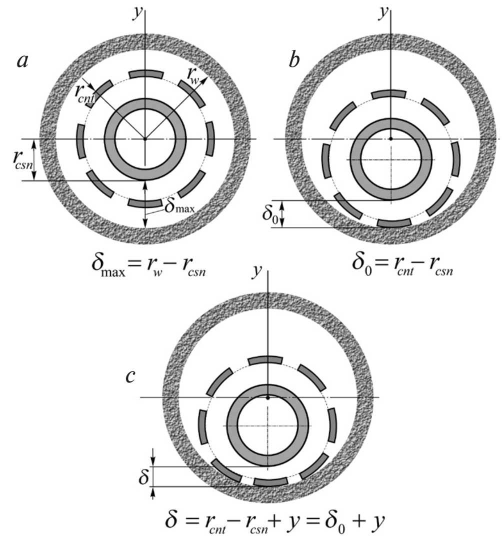

Fig. 1. The cross section of the well with a column equipped with a centralizer:
a – a perfectly centered column; b – location of a column with a centralizer touching well walls; c – location of a bowed column on a deformed centralizer

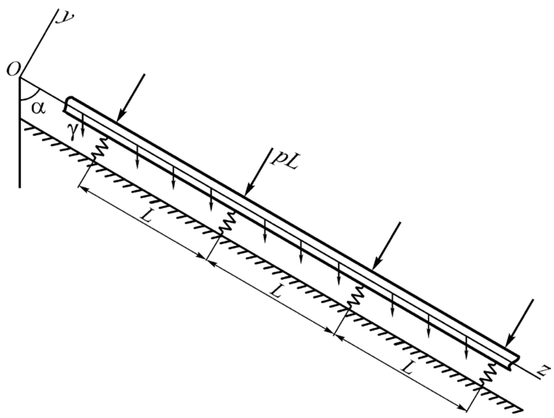

Fig. 2. Scheme of casing loading

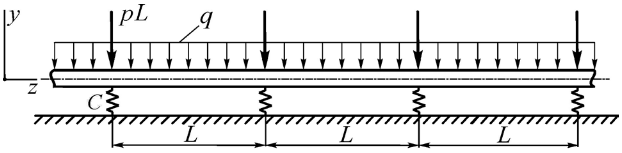

Fig. 3. Computational scheme to study the transverse displacement of a column

The figure features: z – pipe axes; L – the distance between centralizers which is considered to be far smaller than the radius of the well curvature; p – the distributed pressure force; pL– pressing force applied to the centralizer; γ – the weight of a unit length of the pipe in the cement slurry; $q = \gamma \sin\alpha$ – the transverse component of weight force; α – zenith angle of well axis.

Elastic-rigid centralizer has specified characteristics of stiffness or compliance (Fig. 4). At this stage of the study, we believe that depression of centralizers does not change the values of the pressure force p. We also ignore the influence of axial forces on the transverse displacement of the column.

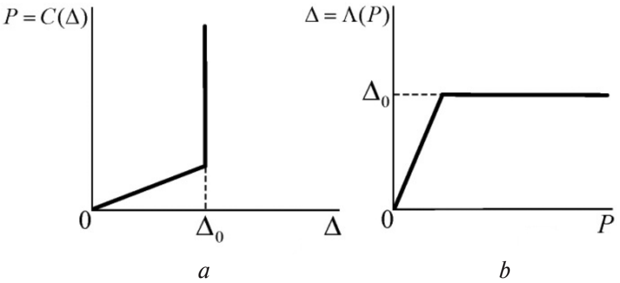

Fig. 4. Model characteristics of non-linear stiffness (a) and compliance (b) of elastic-rigid centralizer

L – periodic boundary problem of a transverse bending of the casing is presented in the following way

$$E_c I_c \frac{d^4 y}{dz^4} + q = 0; \quad z \in \left(kL, \left(k+1\right)L\right); \quad k \in Z; \quad (2)$$

$$Q\left(kL+0\right) - Q\left(kL-0\right) + pL + C\left(y\left(kL\right)\right) = 0; \quad (3)$$

$$M\left(kL+0\right) - M\left(kL-0\right) = 0; \quad (4)$$

$$\vartheta\left(kL+0\right) - \vartheta\left(kL-0\right) = 0; \quad (5)$$

$$y\left(kL+0\right) - y\left(kL-0\right) = 0; \quad k \in Z. \quad (6)$$

Here y is transverse displacement of the column; Q is transverse force; M is bending moment; ϑ is angle of rotation; z is set of integers; $E_c I_c$ is stiffness of the column bending.

Boundary condition (3) relates the response in elastic-rigid support to its displacement, boundary conditions (4–6) ensure the continuity of the moments, rotation angles and displacement when moving through the support.

For further study, condition (3) should be rewritten in terms of the compliance function. Taking into account mutual convertibility $\Lambda(C(x)) = x$, we have

$$y\left(kL\right) + \Lambda\left(Q\left(kL+0\right)\right) - Q\left(kL-0\right) + pL = 0; \quad k \in Z. \quad (7)$$

Given that for any k all sections of the pipe are in the same conditions, from problem (2, 4–7) we switch to a boundary problem on the interval

$$E_c I_c \frac{d^4 y}{dz^4} + q = 0; \quad z \in \left(0, L\right); \quad (8)$$

$$y\left(0\right) + \Lambda\left(Q\left(0\right) - Q\left(L\right) + pL\right) = 0; \quad (9)$$

$$M(0) = M(L); \quad (10)$$

$$\vartheta(0) = \vartheta(L); \quad (11)$$

$$y(0) = y(L). \quad (12)$$

Here (9) is condition of depression of support, additionally loaded by force pL; expressions (10–12) are the periodicity conditions.

Analytical solution. The solution of the problem (8–12) was built by the method of initial parameters. The general solution of the inhomogeneous differential equation (8) provides expressions for the force and geometric factors

$$Q = Q_0 - qz;$$

$$M = M_0 + Q_0 \frac{z}{1!} - q\frac{z^2}{2!};$$

$$\vartheta = \vartheta_0 + \frac{1}{E_c I_c}\left(M_0 \frac{z}{1!} + Q_0 \frac{z^2}{2!} - q\frac{z^3}{3!} \right);$$

$$y = y_0 + \vartheta_0 z + \frac{1}{E_c I_c}\left(M_0 \frac{z^2}{2!} + Q_0 \frac{z^3}{3!} - q\frac{z^4}{4!} \right). \quad (13)$$

Unknown variables Q_0, M_0, ..., y_0 (initial parameters) were obtained, substituting (13) into boundary conditions (9–12)

$$y_0 + \Lambda\left(Q_0 - \left(Q_0 - qL\right) + pL\right) = 0;$$

$$M_0 = M_0 + Q_0 L - q\frac{L^2}{2!};$$

$$\vartheta_0 = \vartheta_0 + \frac{1}{E_c I_c}\left(M_0 L + Q_0 \frac{L^2}{2!} - q\frac{L^3}{3!} \right);$$

$$y_0 = y_0 + \vartheta_0 L + \frac{1}{E_c I_c}\left(M_0 \frac{L^2}{2!} + Q_0 \frac{L^3}{3!} - q\frac{L^4}{4!} \right),$$

or

$$y_0 + \Lambda((q+p)L) = 0;$$

$$Q_0 L - q\frac{L^2}{2!} = 0;$$

$$M_0 L + Q_0 \frac{L^2}{2!} - q\frac{L^3}{3!} = 0;$$

$$\vartheta_0 L + \frac{1}{E_c I_c}\left(M_0 \frac{L^2}{2!} + Q_0 \frac{L^3}{3!} - q\frac{L^4}{4!} \right) = 0.$$

Therefore

$$Q_0 = \frac{qL}{2}; \quad M_0 = -\frac{qL^2}{2};$$

$$\vartheta_0 = 0;\ y_0 = -\Lambda((q+p)L). \tag{14}$$

Expressions (13, 14) give the complete solution of the formulated problem of the bending. In particular, the greatest displacement of the pipe in the module is observed in the middle of the span

$$y\left(\frac{L}{2}\right) = -\Lambda\left(\left(q+p\right)L\right) - \frac{qL^4}{384E_cI_c}. \tag{15}$$

The first summand means the depression of the centralizer under the influence of the pipe weight force as well as pressing force. The second summand shows pipe sagging in relation to the centralizer under the action of the weight force.

Subsequent to the results of (15) from the condition (1) and Fig. 1, *c* we obtain the constraints for the distance between the centralizers.

In fact,

$$\min\delta = \min\left(\delta_0 + y\right) = \delta_0 + \min y = \delta_0 + y\left(\frac{L}{2}\right);$$

$$\min\delta = \delta_0 - \Lambda\left(\left(q+p\right)L\right) - \frac{qL^4}{384E_cI_c}. \tag{16}$$

Then

$$\delta_0 + y\left(\frac{L}{2}\right) \ge \left[\delta\right],$$

and finally

$$\Lambda\left(\left(q+p\right)L\right) + \frac{qL^4}{384E_cI_c} \le \delta_0 - \left[\delta\right]. \tag{17}$$

Given admissible $[\delta]$, from the irregularity (17) it is possible to find the necessary distance between centralizers on a given interval with peculiar q and p. What we have to do is to specify the expression Λ for elastic-rigid centralizer.

Evaluation of stiffness of nonlinear elastic centralizer. On the basis of the solution of problems of contact interaction of the element of the centralizer with the well wall the influence of structural peculiarities of the cyclically symmetric "bow" type centralizers on their rigidity and toughness characteristics was studied [7].

Relationship between the force of interaction between the centralizer and well wall may be presented as follows $P = C_c\Delta$. Real rigidity of the centralizer C_c lies in the range $C_1 \le C_c \le C_2$, where $C_1 = 6\frac{EJ}{l^3} = \frac{1}{2}Eb\left(\frac{h}{l}\right)^3$ is the rigidity of the centralizer with the free sliding of the leaf springs along the axis of the pipe, $C_2 = 256\frac{EJ}{l^3} = \frac{64}{3}Eb\left(\frac{h}{l}\right)^3$ is the rigidity of the centralizer in the absence of sliding of the leaf springs along the axis of the pipe, EJ is bending rigidity of the working element of the centralizer of a rectangular cross section $b \times h$.

In case of equipping the rod of the centralizer by additional stop its radial displacements will be limited

$$\Delta \le \Delta_0,$$

where $\Delta_0 = f - f_0$; f is a boom of a bow-shaped element of the centralizer; f_0 is the height of the stop.

Then non-linear characteristic of this elastic-rigid centralizer will look as follows (Fig. 4, *a*)

$$P = C\left(\Delta\right) = \begin{Bmatrix} C_c\Delta, & \Delta \le \Delta_0 \\ P \ge C_c\Delta_0, & \Delta = \Delta_0 \end{Bmatrix}.$$

Analytical characteristic of the radial compliance of the centering device (Fig. 4, *b*) will be

$$\Delta = \Lambda\left(P\right) = \begin{Bmatrix} \frac{P}{C_c}, & \frac{P}{C_c} \le \Delta_0 \\ \Delta_0, & \frac{P}{C_c} \ge \Delta_0 \end{Bmatrix},$$

or

$$\Delta = \Lambda\left(P\right) = \frac{P}{C_c}H\left(\Delta_0 - \frac{P}{C_c}\right) + \Delta_0 H\left(\frac{P}{C_c} - \Delta_0\right), \tag{18}$$

where $H(\ldots)$ is Heaviside function.

Calculating the distance between centralizers. Using the result (18) of the preceding subparagraph and expression (17), let us set the value for the distance between the centralizers, which provides the gap sufficient for a high-quality cementing $[\delta]$

$$\frac{\left(p+q\right)L}{C_c}H\left(\Delta_0 - \frac{\left(p+q\right)L}{C_c}\right) + \Delta_0 H\left(\frac{\left(p+q\right)L}{C_c} - \Delta_0\right) + \frac{qL^4}{384E_cI_c} \le \delta_0 - \left[\delta\right]. \tag{19}$$

The results of calculations by formula (19) lead to the laws shown in Figs. 5–10.

Let us analyze the quality picture, under the condition that $\delta_0 = 1$; $\Delta_0 = 1/3$; $q/(384E_cI_c) = 1$; $q/C_c = 1$.

Accounting the centralizers elasticity leads to a considerable reduction of the distance between them (curves 2 to curves 1 in Figs. 5, 6). Fitting the centralizer with additional stop increases the allowable distance between the centralizers (curves 3 to curves 2 in Figs. 5, 6) in the range of small acceptable gaps $[\delta] < \delta - \Delta_0$ and does not change the result in case you need a better centering (the range $[\delta] < \delta - \Delta_0$). In the latter case, the stop does not have time to come unto action: curves *2* and *3* merge.

For a given transverse component q from weight force, additional pressing forces do not affect the distance between the centralizers at small gaps (δ), if the stop is activated, and naturally reduce L at large (δ) (Fig. 7). Additional loading q at given pressing force naturally leads to the convergence of the centering devices (Fig. 8).

Influence of the zenith angle for the directional well was analyzed with an allowable gap $[\delta] = \delta_0/3$ being fixed (Fig. 9). With an increase in zenith angle due to transverse component of the weight increase distance L decreases, therefore at $\alpha < 17^\circ$ because of the pressing force buildup p. For $\alpha < 17^\circ$, as well as for significant pressing forces their influence on the distance between the centering devices is mitigated as the stop is put into operation (Fig. 10).

Graphical results were obtained for $\Delta_0 = \delta_0/3$, as well as for the assumption: the rigidity of the centralizer is such that under the action of weight force and in the absence of the pressing force the maximum deflection of the pipe in relation to the supports is equal to the elastic subsidence of the centralizers. Having different basic data we will receive other quantitative indicators, which, however, will not change the established picture.

According to the above method, the calculations of the desired distance between the centralizers obtained from equation (19) at $p = 0$, $q = \gamma \sin\alpha$ for different values of zenith angle and several variants of the admissible gap were performed.

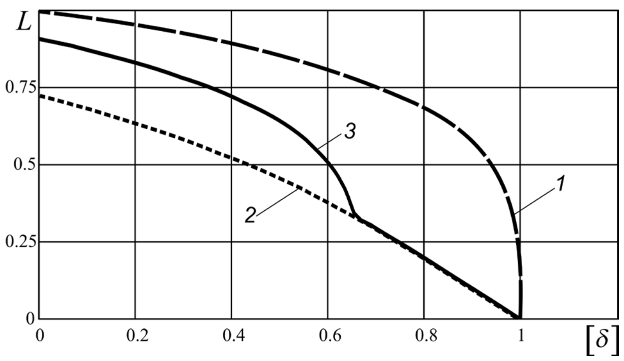

Fig. 5. Dependence of distance between the centralizers and allowable gap in a column loaded by its own weight without additional pressing:
1 – rigid; 2 – elastic; 3 – elastic-rigid centralizer

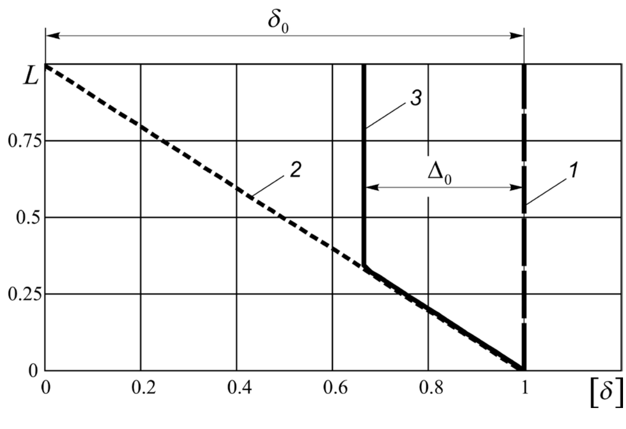

Fig. 6. Dependence of distance between the centralizers and allowable gap in quazivertical site ($q \approx 0$) at pressing forces ($p \neq 0$):
1 – rigid; 2 – elastic; 3 – elastic-rigid centralizer; $\delta_0 = r_{cnt} - r_{csn}$; q – maximum possible radial movement of the centralizers

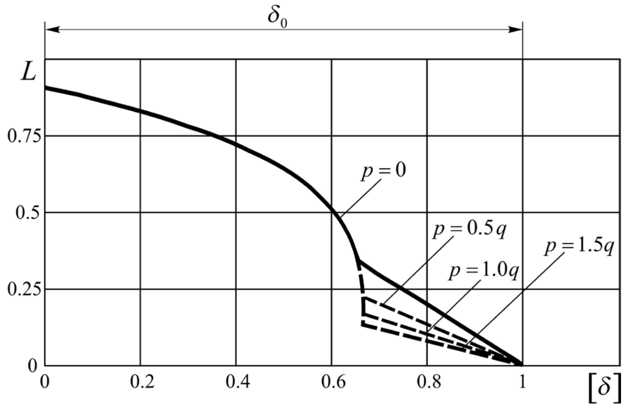

Fig. 7. The influence of additional pressing force on the calculated distance between the elastic-rigid centralizers

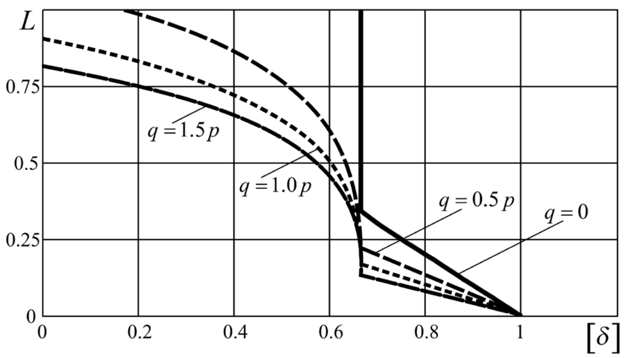

Fig. 8. The influence of the transverse component of the weight of the column on the calculated distance between the elastic-rigid centralizers

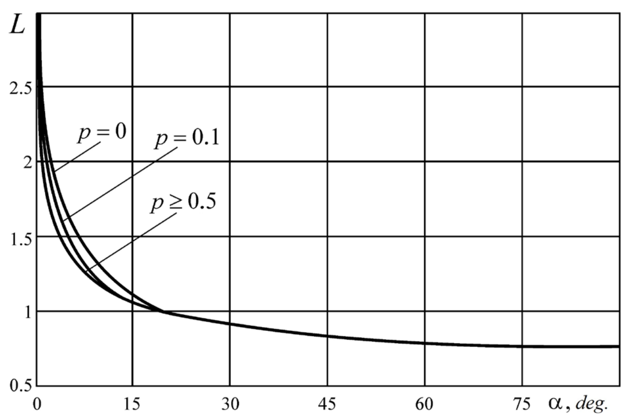

Fig. 9. The dependence of the distance between the centralizers on zenith angle under different pressing forces ($q = \gamma \sin\alpha$)

According to the results of calculations, bigger distances between the centralizers are observed in case of a low-quality centering with a significant deviation from the standard ($[\delta] = 0.4\delta_0$) in comparison with a high-quality centering ($[\delta] = 0.6\delta_0$).

Conclusions.

1. The problem of efficient casing centering was formulated. The aim of the problem was to find the dis-

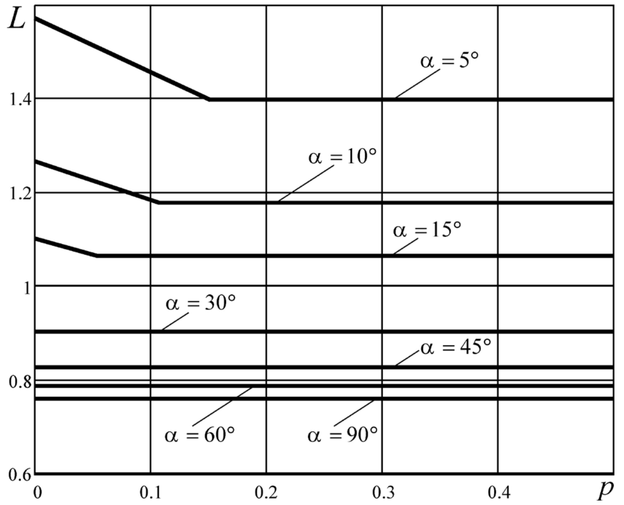

Fig. 10. The dependence of the distance between the centralizers on the pressing force for different zenith angles

tance between the elastic-rigid centralizers to provide the smallest gap between well and casing necessary for high-quality cementing.

2. Based on the solution of the problem of bending of a rod in elastic-rigid supports by the forces of weight and the specified pressing forces, the equation to determine the distance between the centralizers was obtained. The influence of structural peculiarities of the cyclically symmetric "bow" type rod centralizer on the characteristics of their rigidity and strength was taken into account.

3. The dependences of the distance between the centralizers and the allowable gap for a variety of loads acting on the casing were determined. Accounting of centralizer elasticity leads to a significant reduction in this distance. The increased zenith angle due to the increase in the transverse component of weight force leads to the reduced distance between centralizers. This is especially true for small zenith angles. For a large zenith angle, as well as for considerable pressing forces their influence on the distance between the centering devices is offset as the stop is activated. In particular, it was found that the stop of the centralizer provided it is of sufficient strength might guarantee a sufficient gap at high loads on the column.

4. An example of the calculation of the column centering for the real parameters of the well was considered.

Clarification of the obtained results can be achieved considering the influence of axial forces on the bending of the casing, as well as through consideration of spatial pattern of its deformation.

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Мета. Формулювання та розв'язок задачі ефективного центрування обсадної колони у свердловині пружно-жорсткими центраторами з урахуванням складності конфігурації її осі та конструкції центратора.

Методика. Досліджується модель системи „обсадна колона – свердловина", причому колона навантажується двома групами сил: силою власної ваги, розподіленою вздовж осі, та притискними силами, викликаними складною конфігурацією осі свердловини й розподіленими по центрувальних пристроях, якими оснащена колона. Урахований зв'язок ефективності центрування обсадної колони з конструктивними особливостями циклічно-симетричних стрижневих центраторів „ліхтарного" типу та характеристикою їх жорсткості й міцності. Вихідною умовою розв'язку задачі прийнято забезпечення мінімально допустимого зазору в системі „обсадна колона – свердловина".

Результати. На підставі розв'язку задачі про згин стрижня на пружно-жорстких опорах встановлено співвідношення для визначення залежностей віддалі між центраторами від допустимого зазору. Урахування пружності центраторів призводить до значного зменшення віддалі між ними. Зі зростанням зенітного кута внаслідок збільшення поперечної складової сили ваги віддаль між центраторами зменшується, причому для малих зенітних кутів тим сильніше, що більша притискна сила. Для великого зенітного кута, а також для значних сил притискання, їхній вплив на віддаль між центрувальними пристроями нівелюється через те, що спрацьовує упор. Зокрема, встановлено, що упор центратора, за умови його достатньої міцності, може гарантувати достатній зазор при значних навантаженнях на колону. Отримані результати досліджень апробовано інженерними розрахунками для конкретних типорозмірів обсадної труби й свердловини.

Наукова новизна. Уперше отримані нові залежності для розрахунку віддалі між пружно-жорсткими центраторами для оснащення обсадної колони з урахуванням груп факторів, що визначають профіль свердловини та характеристики центратора.

Практична значимість. Одержані результати дають можливість оптимізувати підбір кількості та інтервалів встановлення центраторів на обсадній колоні та, як наслідок, уникнути ускладнень у процесі спуску колони та утворення застійних зон у кільцевому просторі свердловини. Це дозволить виконати якісно тампонажні роботи й сформувати надійне та довговічне кріплення свердловини будь-якої конфігурації.

Ключові слова: *пружно-жорсткий центратор, обсадна колона, зазор, ефективне центрування*

Цель. Формулировка и решение задачи эффективного центрирования обсадной колонны в скважине упруго-жесткими центраторами с учетом сложности конфигурации ее оси и конструкции центратора.

Методика. Исследуется модель системы „обсадная колонна – скважина", причем колонна нагружается двумя группами сил: силой собственного веса, распределенной вдоль оси, и прижимными силами, вызванными сложной конфигурацией оси скважины и распределенными по центрирующим устройствам, которыми оснащена колонна. Учтена связь эффективности центрирования обсадной колонны с конструктивными особенностями циклично симметричных стержневых центраторов „фонарного" типа и характеристикой их жесткости и прочности. Исходным условием решения задачи принято обеспечение минимально допустимого зазора в системе „обсадная колонна – скважина".

Результаты. На основании решения задачи изгиба стержня на упруго-жестких опорах установлено соотношение для определения зависимостей расстояния между центраторами от допустимого зазора. Учет упругости центраторов приводит к значительному уменьшению расстояния между ними. С ростом зенитного угла вследствие увеличения поперечной составляющей силы веса расстояние между центраторами уменьшается, причем для малых зенитных углов тем сильнее, чем больше прижимная сила. Для большого зенитного угла, а также для значительных прижимающих сил, их влияние на расстояние между центрирующими устройствами нивелируется из-за того, что срабатывает упор. В частности, установлено, что упор центратора, при его достаточной прочности, может гарантировать достаточный зазор при значительных нагрузках на колонну. Полученные результаты исследований апробированы инженерными расчетами для конкретных типоразмеров обсадной трубы и скважины.

Научная новизна. Впервые получены новые зависимости для расчета расстояния между упруго-жесткими центраторами для оснащения обсадной колонны с учетом групп факторов, определяющих профиль скважины и характеристики центратора.

Практическая значимость. Полученные результаты дают возможность оптимизировать подбор количества и интервалов установления центраторов на обсадной колонне и, как следствие, избежать осложнений в процессе спуска колонны и образования застойных зон в кольцевом пространстве скважины. Это позволит выполнить качественно тампонажные работы и сформировать надежное и долговечное крепление скважины любой конфигурации.

Ключевые слова: *упруго-жесткий центратор, обсадная колонна, зазор, эффективное центрирование*

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