UDC 622.24.05/62-531.7

DESIGNING OF WELL TRAJECTORY FOR EFFICIENT DRILLING BY ROTARY CONTROLLED SYSTEMS

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The main directions of increasing the efficiency of drilling wells by improving methods for designing profiles of directional and horizontal wells are identified.

The feasibility and necessity of using at drilling with rotary controlled systems the trajectories of directed wells' profiles with continuous curving, that do not contain conjugated sections, on the basis of plane transcendental curves are theoretically substantiated and experimentally confirmed.

An algorithm and software are developed that allow optimal selection of a profile or a trajectory section, taking into account minimization of twisting, bending, compressive and tensile stresses that ensure the efficiency of technical and technological parameters of well drilling.

Key words**:** well drilling, rotary controlled system, trajectory, well profile designing

How to cite this article**:** Dvoynikov M.V. Designing of Well Trajectory for Efficient Drilling by Rotary Controlled Systems. Journal of Mining Institute. 2018. V. 231. P. 254-262. DOI: 10.25515/PMI.2018.3.254

Introduction. The most important criterion for the efficiency of field development, which makes it possible to increase the extraction of hydrocarbons, is the oil and gas recovery factor. An increase in this parameter is possible if the following primary requirements are met: preservation of the natural reservoir properties of the formation during its primary and secondary drilling-in; qualitative cementing of casing strings; high-tech development of the well; application of innovative methods of oil and gas production. The significance of all the mentioned above conditions for increased oil recovery is undoubted. However, it is necessary to distinguish the main one, which allows combining the technical and technological operations of the well construction in one direction – drilling the well according to the project profile, the trajectory of which will ensure the exact drilling-in of the development object, provided by the coordinates.

The increase of the amount of drilling on offshore fields in Russia causes the presence of complexly constructed project profiles of wells containing intervals, which are limited by the radius of curving, or directed rectilinear sections of a large extent, so their construction is based on the use of highly intelligent ground and deep equipment [7].

With the current practice of drilling with the use of modern technical and technological methods for construction of directional wells (rotary controlled systems, rotor-turbine «combined» method, etc.), problems associated with complications and emergencies in the well are noted, which are caused by the absence of an optimized approach to the design of well profiles. The solution of these problems is possible with the development of an algorithm for estimating the project trajectories of the well profiles taking into account the stresses acting on the drilling and casing strings, the downhole operational equipment depending on geological conditions and drilling parameters.

Methodology. Over the past five years, rotary controlled systems have been used in Russia as a techno-technological solution aimed at reducing accidents and improving the quality of well construction with a large vertical deviation Extended Reach Drilling (ERD). The systems enable the orientable drilling along the entire length of the well [5]. The use of rotary controlled systems (RCS) is more than 15 %. However, the presence of complex-built well profiles containing extended directed linear sections, which in turn are connected with curved sections of increasing and reducing zenith angle with an intensity of 0.5 to 2.5 degrees, leads to a loss of drilling string (DS) stability, uncontrollability of torsional vibrations, causing damage to the deflecting (controlling) part of the RCS [8].

When designing the trajectory, the initial and final coordinates of the curved and directed rectilinear (tangential) sections are of great importance. The length of the vertical and the coordinates of tangential sections of a large extent, their connection with the sections of the zenith angle change impose limitations, primarily related to the possibility of drilling, completion, development and selection of the method for further exploitation of the well. During the drilling process, the main requirement is to get the bottomhole assembly (BHA) into the allowance circle, indicated by the technical assignment. In this case, it is necessary to create a model of the profile trajectory that could ensure that the bit load is adjusted by regulating the frictional forces against the borehole wall, and also to control and manage the tensile, compressive and torsional stresses that limit the range of working capabilities of the drilling string operation [10, 12]. This limitation is due to the technical characteristics of the drilling string, its strength properties, which are crucial in calculating the length and intensity of curving - justifying the permissible radius of curved sections in the trajectory of the borehole profile [1]. The presented analysis of the studies confirms the need for research and development of an algorithm for estimating the trajectories of energy-saving profiles of directed and horizontal wells, as well as the methods of their implementation with the use of the RCS [3, 11].

The method of research and evaluation of the developed model's reliability analyzes the following:

- existing types of profile trajectories and methods for their design;
- geological and physical-mechanical properties of rocks, as well as technical and technological methods of drilling wells, taking into account the complexity of the trajectory;
- inconsistencies in the design (calculated profiles) with the actual trajectory of the drilled well;
- methods for estimating the loading of a drilling string and methods for regulating drilling parameters that ensure a reduction in emergency rate in a well.

Modelling of calculation experiment. The object of the computational experiment are well profiles whose trajectories have a continuous curving with a given curving intensity represented by one line without conjugation of rectilinear sections and sections with increasing curving, as well as lines having conjugation with a vertical section. The conjugation of some lines with a vertical section is caused by the impossibility of their construction from the wellhead to the designed depth and the angle of the entry into the reservoir. These lines are performed on the basis of four types of transcendental curves: tractrix, biclothoid, brachistochrone and tangential profile. Computational experiments included data entry and calculation of the basic parametric equations of the curves. Initial data for the construction of profiles: deviation from the vertical 450 m; the depth of the well along the vertical is 2620 m; the minimum permissible radius is 300 m; angle of entry into the reservoir is 65 degrees. On the basis of these data, the radius of curving is calculated as a function of the deviation and the depth of the well along the vertical for all the transcendental curves under consideration.

Figure 1 shows the dependences of the curving radius : *a* – on the deviation and the calculated profile on the basis of the parametric equations of the curve – the tractrix; *b* – on the depth of the well and the calculated tangential profile; *c* – on the depth of the well at calculating the trajectory along the parametric equations of the curve – biclothoid; *d* – on the depth of the well and the calculated profile, constructed from the parametric equations of the transcendental curve – brachistochrone.

Figure 2 shows the calculated profiles of wells, constructed on the basis of parametric equations of curves (biclothoid, tractrix, tangential profile and brachistochrone) for given initial conditions [2]. The calculation results of the main parameters of the well profiles: the minimum radius of biclothoid is 425 m, the tractrix – 300 m, the tangential profile – 400 m, brachistochrone – 425 m; the minimum radius at the depth of the biclothoid is 2385 m, the tractrix – 2620 m, the tangential profile – 2156 m, the brachistochrone – 2318 m; the depth along the trunk of the biclothoid is 2828 m, the tractrix is 2738 m, the tangential profile is 2851 m, the brachistochrone is 2810 m.

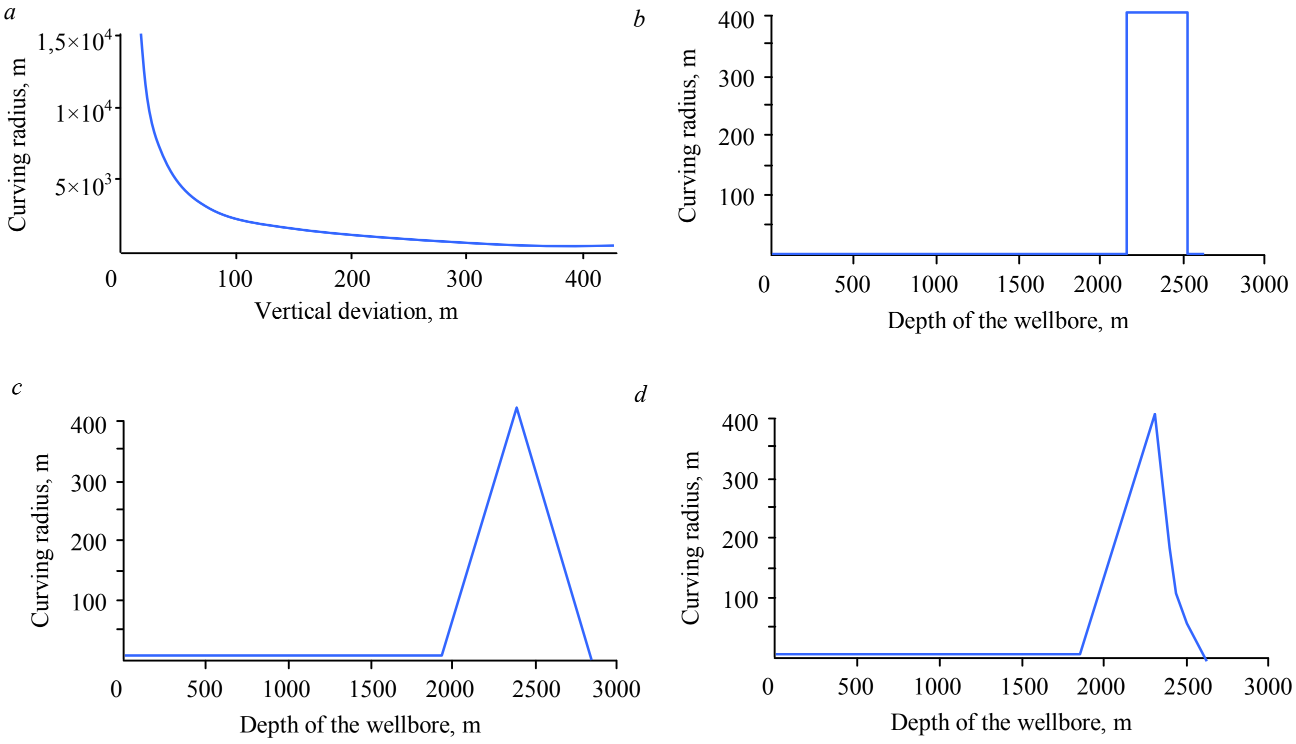

Fig.1. Curving radius dependencies

Given the equivalent initial conditions for plotting the profile trajectory (vertical depth, curving intensity, entrance angle into the reservoir, deviation from the vertical), the smallest borehole depth along the trunk contains a profile designed by the tractrix. It can be seen from the calculations that the length along the trunk of the borehole is 100 m less than other profiles. Tangential profile has the most positive indicator of the radius, as its minimum radius was not more than 400 m, and the curving intensity setting begins with a minimum depth compared to the other profiles – 2156 m. However, it also has peak intensity values in the range of 2200-2500 m. The profile, designed according to the tractrix dips, does not change the intensity. The change in radius occurs uniformly from 300 m to the bottomhole of 2465 m, without exceeding the criterion of the zenith angle setting intensity. This indicator affects the reduction of the resulting stresses acting on the BHA during the downhole operations (DO) and drilling of the well.

Taking into account the calculated well profiles, the investigation of the torque and strength parameters of the drilling string operation during drilling and DO was performed using the LANDMARK software module WELLPLAN™ Torque / Drag. Quantitative estimates of the wells trajectory with an array of data reflecting the torque and strength performance of the BHA and the drilling tools as a whole for the main parameters of the drilling modes were obtained.

The obtained results of the experiments were evaluated based on the equivalent drilling conditions, design and parameters of the washing liquid. Well design:

Casing type	Bit diameter, m	Casing diameter, m	Depth of casing descent, m	Depth of casing descent (trunk), m
Surface	0,293	0,228	700	0-780
Production	0,212	Uncased	2509	0-3209

Composition and characteristics of BHA (element name, diameter, model): bit, 0,212 m, PDC FXD65R; rotary controlled system, PD 675 X5 AB 8 3/8" Stabilized CC; protective crossover sub, 0.175 m, Alloy 25; logging tool, 0.175 m, Alloy 25; measuring tool at drilling, 0.173 m, 15LC MOD , 5 1/2, non-magnetic bypass sub, 0.177 m, 15LC MOD, 5 1/2, non-magnetic drill collar, 0.171 m, 4145H MOD, drill pipes, 0.127 m, NC50 (XH), drill collar, 0.127 m, NC50 hydromechanical jar, 0.173 m, 4145H MOD, drill pipes, 0.139 m, NC50.

The following rheological characteristics of the drilling mud were used during the experiments: the temperature of the solution was 21 °C; base density 1140 kg/m^3; plastic viscosity 16.35 mPa·s; dynamic shear stress is 2.2 Pa.

Drilling parameters: flow rate 32 l/s; load on the bit from 50 to 100 kN; pressure on the manifold 26 MPa.

Results. As a result of the computational experiments, the energy characteristics of the drilling tool were obtained: the torque on the top drive during drilling (Fig.3); tensile stress at DO; bending stress during drilling (Fig.4); pull-up of the wire rope (weight on the hook at DO); fatigue factor.

The minimum value of the torque at the wellhead is the trajectory along the tangential profile (9.2 kN·m), and at the bottom, as well as for the tractrix, not more than 4.0 kN·m. The torque of the profile designed by the tractrix at a depth of 3200 to 2200 m is the smallest on this interval in comparison with other profiles. For example, the torque in the mentioned interval designed by the tractrix is less by 2.6 kN·m in comparison with the profile of the brachistochrone equations and by 1.6 less than the tangential profile. In this case, at the bottom of the BHA, when the DS rotates, the lowest torque index will correspond to a well whose profile in the lower part of the curved section has a smooth change in the radius of curving. In this case, a profile designed according to the parametric equations of the tractrix has this smooth distribution of curving. Such a positive effect will reduce the bending and torsional stresses in the compressed part

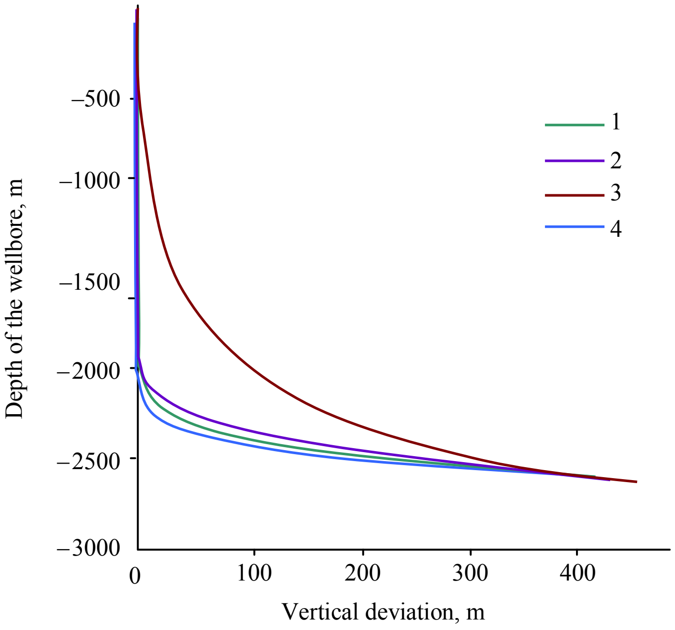

Fig.2. Estimated trajectories of well profiles based on parametric equations of curves: biclothoid (1), brachistochrone (2), tractrix (3), tangential profile (4)

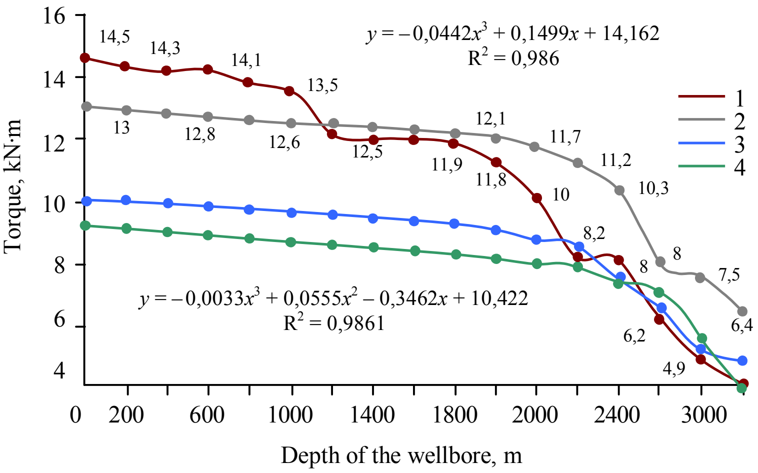

Fig.3. Dependence of the torque change on depth of the wellbore
1 – tractrix; 2 – brachistochrone; 3 – biclothoid; 4 – tangential profile

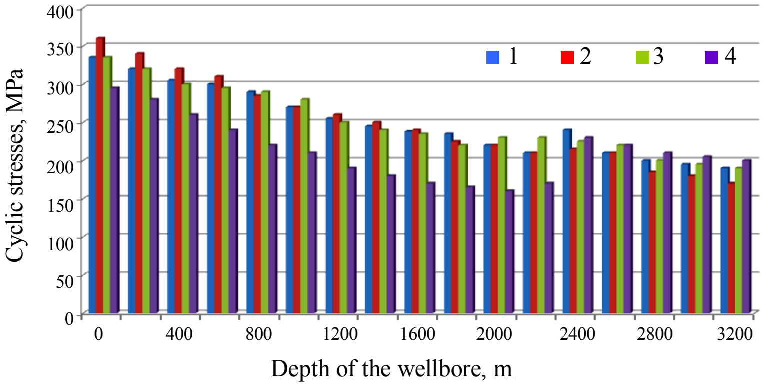

Fig.4. Change of cyclic stresses depending on depth and profile type
1 – biclothoid; 2 – tractrix; 3 – tangential profile; 4 – brachistochrone

of the drilling tool. It should be noted that a smooth change in the curving almost to the wellhead leads to an increase in the torque in the upper section of the DS.

For the steel from which the DS and BHA are made of, the durability limit at amplitude change of the bending stresses cycle varies from 930 to 950 MPa.

The results of the cyclic stresses study showed that maximum stresses in the upper cross section of the DS in the well are experienced by a trajectory, the profile of which is designed according to the tractrix and equal to 360 MPa. Minimum stresses (no more than 295 MPa) at the wellhead are applied to a tool with a well profile – brahistochrone. Stresses in the DS with the borehole profiles of biclothoid and tangential were 335 MPa.

In the middle part of the well trajectory (the interval from 1200 to 2200 m), the stresses acting on the DS whose profile is designed on the basis of the biclothoid, tangential and tractrix curves have the same values from 260 to 220 MPa. In this case, the stress in the indicated interval in the borehole with brachistochrone has the lowest value – no more than 160 MPa. From the depth of 2200 to the bottomhole, the least stress is experienced by the tool in the well with the tractrix. The stresses acting on the DS with this profile in the lower interval are no less than 10 % lower than in other profiles and are: tractrix – 170, brachistochrone – 200, biclothoid and tangential profile – 190 MPa.

When carrying out calculational experiments, the equivalent stresses (VonMises) and the fatigue factor at rotating DS with and without tool load were also analyzed. Analysis of the fatigue study results of DS showed that in the upper interval from the wellhead to 600 m for the profiles (biclothoid, tractrix and tangential), the coefficient is zero. Moreover, for a profile designed according to the brachistochrone, the fatigue factor almost to a depth of 1900 m does not exceed 0.2. This confirms that the smallest amplitudes of variable compressive and bending stresses cycles act on the drilling tool in the wellbore, whose profile is represented by brachistochrone. At the same time, from 2000 to 3200 m, the fatigue factor increases in all well profiles and is equal for: brachistochrone – 1.8, biclothoid – 1.7, tractrix – 1.6. The lowest coefficient corresponds to the tangential profile – no more than 0.8, which predetermines the possibility of DS long life cycle in the well.

The largest equivalent stresses at the wellhead were observed in the borehole with the profile designed by the tractrix, and reached 440 MPa, and axial stresses – 500 MPa. At the same time, in the interval of 2200-3200 m in the wellbore, the profile trajectory of which is represented by the tractrix, a decrease in stress was observed. For example, in the interval 2600-2800 m, the axial and equivalent (resulting) stresses that are exerted on the BHA while lifting are: tractrix – 200, brachistochrone 250, tangential profile – 230, biclothoid – 250 MPa. This indicator once again confirms that the DS in the well, whose profile is represented by the tractrix, undergoes the lowest twisting stresses in the lower interval (the section of BHA operation).

Computational experiments also provided for the study of the forces (tension) acting on the DS in the DO, the angle of twisting (spiral bending) of the tool during drilling. Analysis results of the studies defining the dependence of tension, sinusoidal bending, and also the twisting angle of the DS at the DO and drilling on the depth of the well with different profiles showed that the maximum tension in the upper cross section of the tool corresponds to the trajectory designed according to the parametric equations of the tractrix, and amounted to 1100 kN. For the remaining profiles: brachistochrone and tangential – 990, biclothoid – 960 kN. The greatest weight loss of the tool due to the spiral bending (in the range from 2000 to the bottomhole) corresponds to the profile containing brachistochrone, and amounted to more than 1000 kN. For the other profiles, the twisting angle is no more than 200 kN. It should be noted that the axial load on the bit of 100 kN for the brahistochrone profile is possible from the depth (the interval of the compressive load acting on the tool) of 1600 m. The analysis of the strength parameters for the remaining profiles showed that the compressed part of the drilling string is much lower and varies at a depth of 2150-2250 m. The positive side of the brachistochrone profile in the study of sinusoidal bending should also be noted. This form of bending in the profile in question begins at a depth of 1800 m and extends to the bottomhole. In this case, the loss of stability is practically absent in the interval from 0 to 1800 m. In the remaining profiles, the beginning of a sinusoidal bend corresponds to an interval of 600-3200 m.

At the final stage of the computational experiments, estimations of the intermittent hydraulic resistances were made, depending on the type of profile in question. Studies have shown that the pressure drop at the wellhead for all profiles was almost the same and amounted to 17.6 - 18.0 MPa. The pressure at the bottomhole with regard to pressure drop in the bit was 40 MPa and in the annulus at a depth of 3200 m no more than 33 MPa.

As a result of the conducted research, the drilling tool's intermittent stresses were determined during its operation. However, it is not possible to evaluate and select the best trajectory from the available four alternatives of the well profiles considering only the interpretation of the calculated output data, since each profile has a qualitative positive result in a certain drilling interval.

Method of well profiles analysis. To solve the task aimed at creating a methodology for selecting the best profile from the previously known several (trajectories, sections of profiles) alternatives that have quantitative (numerical) or qualitative results for a set of parameters, a multicriterial method of expert evaluations is applied.

To optimize profiles according to established criteria and assigning their levels, the method developed by the American mathematician Thomas Saati was used in the work [9]. When setting the task of choosing an alternative with a large number of estimates, the method of hierarchical analysis (MHA) is most applicable. One of the main advantages of MHA is the ability to take into account both quantitative and qualitative assessments. At the first stage of applying the MHA, the choice problem is structured as a hierarchy – a set of parameters that have the value of the best alternative [4].

Of all the entire data set, obtained as a result of modeling in the LANDMARK system, the WELLPLAN™ Torque / Drag module, the minor parameters (tortuosity of the trunk, rugosity, azimuthal deviation, etc.), which do not fundamentally affect the decision-making of the profile choice, were eliminated. The remaining parameters (the curving intensities and radii of the trajectory sections, the technical characteristics of the equipment materials, the characteristics of the objects to be drilled-in and the locations and characteristics of the equipment to be installed for subsequent operation of the well, etc.) were evaluated by the degree of their influence on the decision-making to choose the alternative in accordance with the MHA, i.e. assigning them a weight value *w*.

The essence of this method is in presenting estimates of m alternatives for a certain number of *n* parameters in the form of a rectangular matrix *P* of dimension $m \times n$ and its subsequent statistical processing.

Each parameter at the criterion level has its own weight w_i, and their sum is equal to one:

$$\sum_{i=1}^{n} w_i = 1. \tag{1}$$

By default, if all parameters are equally important, then their weight is assumed to be equal to

$$w_i = \frac{1}{n}. \tag{2}$$

After determining the weights of the parameters, the selection problem is structured as a hierarchy. In general, the hierarchy is built from the top through intermediate levels – the criteria to the lowest level on which the set of alternatives was located (Fig. 5).

At the final stage of the MHA, each i alternative is assigned a numerical value x_i, which characterizes the estimation of the i alternative by all the criteria *n*. An alternative with the highest estimate of *x* is considered the most preferable.

In the process of research, two types of criteria for evaluating the trajectory of profiles are used: quantitative and qualitative. Qualitative criteria are based on the subjective evaluation of the well profile by an expert. Quantitative criteria assume the definition of the values of quality parame-

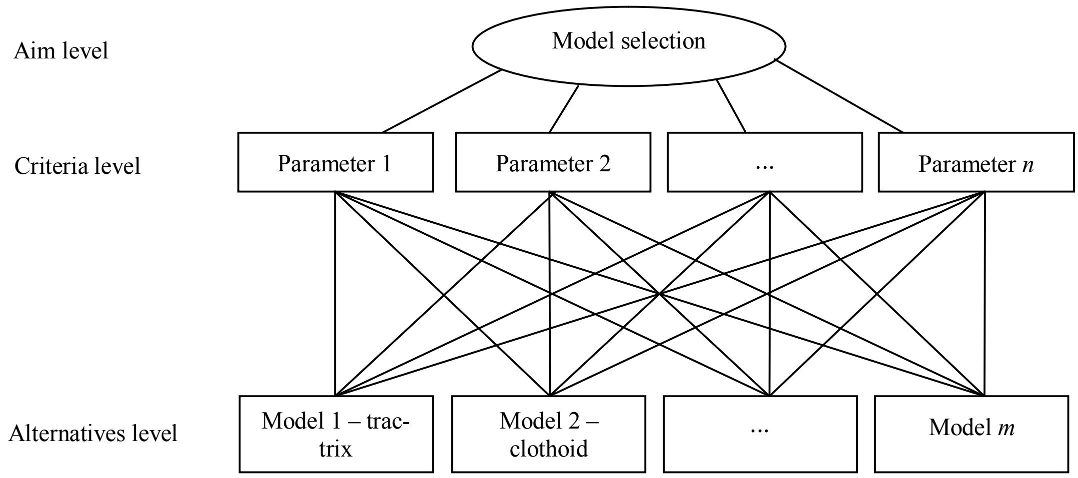

Fig.5. Hierarchy of optimal model selection

ters that numerically reflect the similarity degree of the constructed model and the model having reference values for the parameters considered. If the accuracy of a parameter when selecting a model implementation is of great importance, then it is assigned a larger weight w_i.

After determining the weights of the investigated profile parameters, estimates are obtained for each model (alternative) considering each of the parameters. If any parameter does not allow to estimate the alternative with a numerical value, then a matrix of preferences for x alternatives for each parameter is constructed based on the expert's poll using a special intensity scale of relative importance. The poll is performed by pairwise comparison of alternatives according to the qualitative criterion being considered.

The elements of the matrix x should have the following property:

$$x_i = \frac{1}{x_{j,i}}. \tag{3}$$

After the construction of the preference matrix, it is processed to obtain the normalized weights of the factors being compared. For each of the parameters n of the matrix there is a normalized component of the own vector w_i of the matrix x by the formulas:

$$w_i = \sqrt[n]{\prod_{j=1}^{n} x_{i,j}}\ , \tag{4}$$

$$w_{inorm} = \frac{w_i}{\sum_{i=1}^{n} w_i}. \tag{5}$$

Then the maximum own value of the preference matrix x is calculated

$$\lambda_{\max} = \sum_{j=1}^{n}\left(\sum_{i=1}^{n} x_{i,j}\right) w_{jnorm} \tag{6}$$

and condition is checked

$$\lambda_{\max} \geq n. \tag{7}$$

If condition (7) is met, then the matrix index of consistency x is found

$$I_{\text{c}} = \frac{\lambda_{\max} - n}{n-1}, \tag{8}$$

$$I_c \leq 0{,}2. \qquad (9)$$

If conditions (7) and (9) are satisfied, then $w_{i\text{-norm}}$ values are taken as estimates, otherwise the matrix x is formed anew, with higher requirements for estimating excellence.

The calculation of subjective estimates by formulas (3)-(9) can be applied to the evaluation of well profiles by some qualitative criterion, or by forming weights of parameters, having learned from the customer (field user's geological service) which of the profile parameters are more important for him.

After constructing the hierarchy of alternative choice, an algorithm is proposed for choosing the profile of the well (Fig.6).

On the basis of the proposed algorithm, a computer program for multicriterial analysis of well profiles was developed [6], the profiles' trajectories of the four wells under consideration were analyzed. Next models are presented: tractrix, tangential profile, biclothoid, brachistochrone. The investigated parameters were torque-strength characteristics of the drilling tool in the well. The choice of the parameter for the implementation of the model was based on weighting factors.

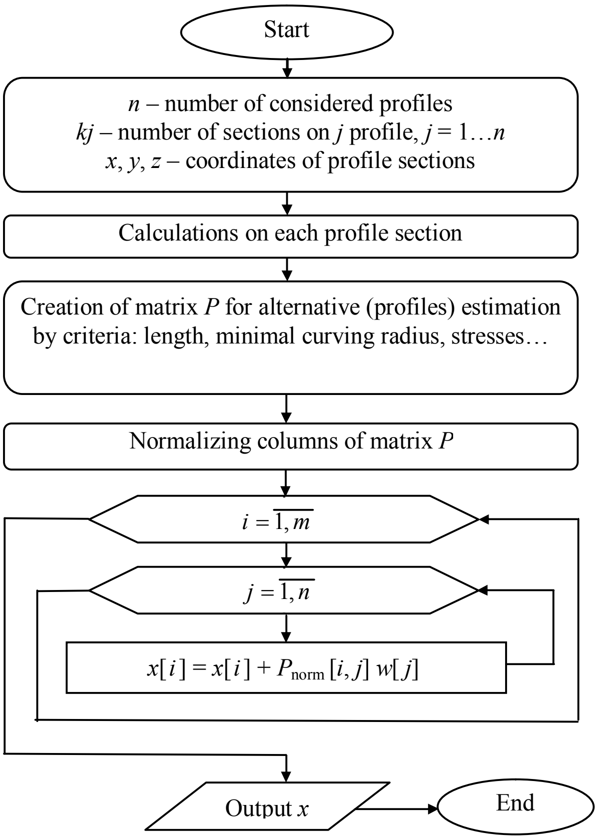

Fig.6. Block diagram of the analysis algorithm for well profiles on the basis of MHA

As a result of the calculations, performed on the basis of the presented algorithm, taking into account qualitative and quantitative criteria, it is revealed that the tractrix has the smallest deviation from the parameters of the reference model, and therefore is the most suitable for drilling a well with rotary controlled systems.

Results

1. As a result of conducted analysis, quantitative estimates of well profiles calculated on the basis of parametric equations of curves (biclothoid, brachistochrone, tractrix, tangential profile) were obtained that reflect the torque-strength performance of the drilling tool, taking into account the equivalent drilling conditions, structure and drilling mud properties.

2. Computational experiments did not allow accurate evaluation and choosing the most suitable trajectory represented by transcendental curves, since each profile has a qualitative positive estimate in a certain drilling interval.

3. Application of the developed algorithm, taking into account qualitative and quantitative criteria for estimating the profile trajectory, allows identification of the smallest deviation from the parameters of the reference model and determine the most suitable model for drilling a well with given initial conditions (vertical depth, deviation, intensity, etc.) using rotary controlled systems.

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The paper was received on 19 July, 2017.
The paper was accepted for publication on 26 Februaru, 2018.