sciendo

Management Systems
in
Production Engineering

2020, Volume 28, Issue 3, pp. 189-195

Date of submission of the article to the Editor: 01/2020
Date of acceptance of the article by the Editor: 06/2020

DOI 10.2478/mspe-2020-0028

# EVALUATION THE STRESS-STRAIN STATE OF PUMPING EQUIPMENT IN THE CURVILINEAR SECTIONS OF THE WELLS

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**Abstract:**
The development of oil fields at a late stage is characterized by a number of complications that determine the features of the operation of downhole equipment in pumping units. The use of electric-centered pumps in wells with intervals of increased curvature intensity requires a preliminary analysis of the possibility of lowering and operating the equipment at design depths. The aim of research is development of a new approach to evaluation the stress-strain state of pumping equipment, taking into account the features of the inclinometry of the intervals of its location. The analysis of the results of previous studies of the influence of the well profile on the operation of pumping equipment and recommendations for ensuring its performance is carried out. Given the possibility of operating equipment with limited levels of deformation, a mechanism is proposed for evaluation its stress-strain state using software products based on the finite element method. The reliability of the results is confirmed by comparison with those obtained in the course of analytical studies performed according to a previously tested methodology. Application of the proposed approach will allow to assess the level of deformation of individual elements of the equipment installations, taking into account their design features and the results of inclinometry.

***Key words:*** *well, inclinometry, pumping equipment, deformation, stress*

## INTRODUCTION

The development of oil fields at a late stage is characterized by a high water cut of the product, the content of mechanical impurities and free gas in its composition, and the formation of organic and inorganic deposits in the trunk. In order to maintain the established production volumes at such fields, there is a need to increase the depth of descent of pumping equipment. Limitations regarding the possibility of implementing such measures arise in bored wells and wells with local intervals of increased curvature intensity. The main complications during the operation of sucker rod pump installations (SRPI) in such wells are caused by an increase in the friction forces [10, 18]. As a result, intensive wear of the rods, rod couplings and pump compressor pipes (PCP) is observed, which reduces the time of their operation. Axial loads on the rod string at the point of its suspension when walking upward increase [2, 11]. The friction of the rods in the liquid during the down stroke can lead to their “freezing” [9]. As a result, the work is accompanied by shock loads and causes the occurrence of vibrations. To improve the working conditions of pump rods, some authors propose the use of elastic suspensions of a polished rod and shock absorbers of a rod string [6, 17]. Despite this, the influence of the above factors leads to a number of malfunctions of the SRPI drives [8].

Wells in the Western region are characterized by the presence of intervals with the intensity of curvature, which exceeds the recommended design values. In this regard, it is quite common today to equip such wells with electric centered pump installations (ECPI). At the same time, the ECPI use is justified, but their operation is also accompanied by complications.

There are a lot of factors affecting the ECPI operation. In total, they should be divided into groups. The first is made up of the geological ones already mentioned, and the second group needs to be attributed to factors due to the design features of the borehole and the ECPI. All of them individually and together determine the characteristics of the ECPI operation.

## ANALYSIS OF OPERATION FEATURES OF ELECTRIC CENTERED PUMP UNITS UNDER COMPLICATED CONDITIONS

The main indicator of equipment operation is the mean time between failures, which reflects the loss of working ability due to wear and tear. The data obtained by the authors of [12] on the number of accidents, depending on the SRPI operating time indicate that they occur mainly in the initial period of operation (up to 100 days). With an operating time of more than 400 days, emergency failures become rare. This indicates that emergency failures do not have a direct relationship to the wear of individual units, and are fatigue-like. It is also noted that in the intervals of an increase of well curvature of 2 degrees or more per 10 m, the number of failures increases. The reason is the occurrence of bending and jamming loads acting on the housing units of pumping units (PU) and power cable. Also, a problem in the operation of deviated wells with the help of ECPI is the curvature of the rotor, which leads to an increase in vibration exposure. Increased vibration displacements cause alternating stresses in the area of the units connecting with each other and with the tubing, causing their destruction.

Theoretical studies [13] establish that when working on the curved area of the well with an inclination of more than 5 degrees, the ECPI bends under its own weight. This causes vibration and lateral runout in the casing. An additional bending moment on the PU creates the weight of the PCP string (with fluid). In the interval of zenith angle increment, this moment increases the deflection of the equipment and assumes the maximum value when the wellbore is inclined from 5 to 30 degrees. Based on the justification, the value of the permissible curvature of the wellbore in the interval of the PU location is found that, in addition to its overall dimensions and the inner diameter of the casing string, these values depend on the zenith angle and on the nature of the profile (increasing or decreasing of the zenith angle). For wells with incline of more than 30 degrees, the value of the permissible curvature can be taken equal to 3 degrees per 10 m, regardless of the PU standard size and the diameter of the casing.

In article [4], the result of an analysis of PU failures for one of the oil fields is presented, in particular due to a break in the shaft. The analysis shows that break of shafts occur in various elements of the equipment. At the same time, 44% of fractures are plastic and 56% of failures are associated with fatigue fracture of the shafts. Most fatigue fractures (84%) occur along the splines in the area of the coupling joint. Fatigue fractures are consequence of the action of vibration loads, including due to wear of the radial joints of the working bodies. The average running time through a fatigue fracture is 74 days. At the same time, the operating time of more than half of the SRPI (53%) does not exceed 40 days.

The results of the analysis of field data due to the large number and a wide variety of factors affecting the operational reliability of PU are often of a qualitative nature and do not allow strictly evaluation the permissible limits for changing the profile of wells. However, for reasons of ensuring the operability of the downhole equipment, the profiles of directional wells should contain sections with a curvature intensity of more than 2 degrees per 10 m when increasing the inclination angle and 3 degrees per 10 m in the area that is controlled to decrease it. The difference in these values is explained by the authors of [7].

Summing up the analysis, it should be noted that for a long time, studies have been carried out regarding the requirements for descent and the location of the ECPI. In the works, the geometric conditions of the inclusion of individual sizes in the casing are determined. In this case, the curvature is considered permissible if the PU fits freely into the wellbore or is in a deformed state, which is characterized by an arrow deflection of the shaft not more than 0.0002 ... 0.0003 of its length.

To date, the minimum allowable gap between the PU and the casing, which guarantees its trouble-free descent and ascent, has been found and justified taking into account the results of experiments and production experience. For various combinations of pump and motor parameters, it is indicated by the manufacturers in the technical requirements. In particular, leading manufacturers recommend a minimum clearance between the casing string and the PU in the range of 3 to 6 mm.

Direct operation of equipment in curved sections is regulated by permissible deflection. The interval for the PU installation is selected as far as possible without bends, that is, with constant values of zenith angles. However, quite often this interval is due to the curvature due to the presence of azimuthal deviations, despite the fact that the zenith angles remain unchanged. Thus, the PU takes shape in accordance with the spatial curvature of the well interval. The intensity of the curvature of the pump can be less than the intensity of the curvature of the wellbore, or exceed it. In general, the analysis of the well inclinograms indicates that the intervals for placing the PU without transverse bending are quite limited in some cases.

## SUBSTANTIATION OF THE NEED FOR EVALUATION OF THE STRESS-STRAIN STATE OF THE PUMPING EQUIPMENT TAKING INTO ACCOUNT THE INCLINOMETRY OF INTERVALS OF ITS PLACEMENT

In any case, the success of the lifting operations depends on the results of inclinometry and the accuracy of evaluation the influence of the profile of certain intervals of the well on the features of the formation of the PU stress-strain state based on their design.

The possibility of using modern software products to study the stress-strain state of pipe columns is indicated in publications [1, 15]. In [19], the results of modeling the deformed state of a drill pipe string using the finite element method are presented. It is worth noting that the studies relate to a randomly oriented space section of the well, however, only straightforward.

According to ECPI, it should be noted that the article [3] shows the results of the numerical solution of mathematical 3D models in the SolidWorks program of splined shaft joints for straight-line and involute types. The places of the largest stress concentrations, the constructed dependences of the installation operation time to failure from shaft deflection, are determined. A comparative analysis of the fatigue strength of shafts using splined joints of both types is carried out. However, the obtained results are of practical value only when compared with the actual values of shaft deflections with operating conditions.

In view of the foregoing, the aim of the research is to create the prerequisites for a quick and proper assessment of the stress-strain state of pumping equipment as a part of ECPI during its operation in a given interval of the well. Simulation using the finite element method to confirm the reliability of the results requires comparison with similar experimental or analytical studies [5, 20]. Given the complexity of the experiment, it is proposed to use the results of studies using a previously tested methodology for comparison [14].

For research, the results of the inclinometry of the well interval are used and a number of simplifications are made. PU is replaced by a cylinder with a diameter of 121 mm, which corresponds to the conditional size of the pump with a diameter of 102 mm. The stiffness is determined by the results of a preliminary experiment with a pump and electric motor section and is accepted as an average value.

## METHODOLOGY OF ANALYTICAL STUDIES OF STRESS-STRAIN STATE OF EQUIPMENT

According to the aforementioned methodology [14], the PU is modeled as a weighty long-length object of circular cross-section with a given estimated moment of inertia. According to the calculation scheme (Fig. 1), the upper extreme section of the model is completely fixed, and the lower one is fixed by a hinged movable support. It is also envisaged the possibility of PU contact with the wall of the well in the vicinity of the points of inclinometry and the occurrence of appropriate reactions.

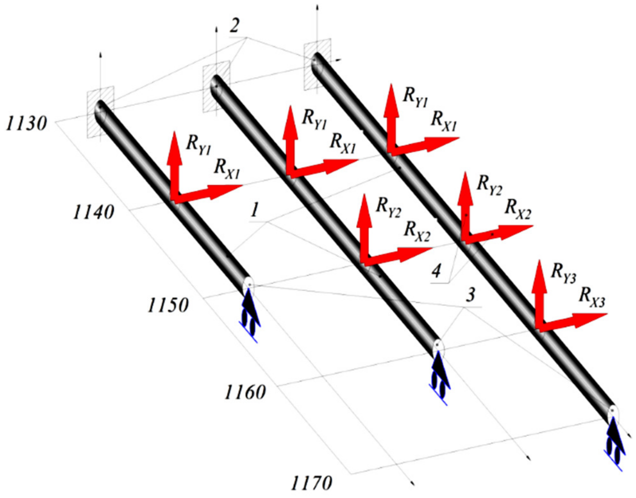

*Fig. 1 Design schemes of PU models*

According to a preliminary analysis of the results of inclinometry, a research area is selected, the beginning of which corresponds to the mark of 1130 m. Therefore, to simulate different PU length, the initial section of the model is placed at the well point at a depth of 1130 m, and the another one – at the point of the well at depths of 1150, 1160 and 1170 m (Fig. 1).

Moreover, for all cases, the analysis of the stress-strain state of PU is performed using the fundamentals of the mechanics of flexible rods [16], according to which its elastic axis is described by a system of vector differential equilibrium equations:

$$\frac{\tilde{d}\vec{Q}}{d\varepsilon}+\vec{\chi}\times\vec{Q}+\vec{P}=0 \tag{1}$$

$$\frac{\tilde{d}\vec{M}}{d\varepsilon}+\vec{\chi}\times\vec{M}+\overrightarrow{e_1}\times\vec{Q}+\vec{T}=0 \tag{2}$$

$$\vec{M}=A\left(\vec{\chi}-\overrightarrow{\chi_0^{(1)}}\right) \tag{3}$$

$$L\frac{\tilde{d}\vec{\vartheta}}{d\varepsilon}+L_2\overrightarrow{\chi_0^{(1)}}-A^{-1}\vec{M}=0 \tag{4}$$

$$\frac{\tilde{d}\vec{u}}{d\varepsilon}+\vec{\chi}\times\vec{u}+(l_{11}-1)\overrightarrow{e_1}+l_{21}\overrightarrow{e_2}+l_{31}\overrightarrow{e_3}=0 \tag{5}$$

where:

$\vec{Q}$and $\vec{M}$ – vectors of internal forces and moments;

$\varepsilon$ – dimensionless coordinate;

$\vec{P}$, $\vec{T}$ – vectors of external forces and moments;

$\vec{\chi}$, $\vec{\chi}_0^{(1)}$– vector of the current and initial curvature of the rod;

$\overrightarrow{e_1}, \overrightarrow{e_2}, \overrightarrow{e_3}$, – unit vectors of the associated coordinate system (a moving coordinate system, the direction of the axes of which coincides with the direction of the main axes of inertia of the rod)

$A$ – rod stiffness matrix,

$L$, $L_1$ – transition matrices between vector bases,

$\vec{\vartheta}$ – vector of the rotation angle of the associated coordinate system relative to the initial position;

$l_{11}$, $l_{21}$, $l_{31}$ – elements of the matrix *L*.

In turn, the vectors $\vec{P}$ and $\vec{T}$ are determined by the formulas [1]:

$$\vec{P}=\ \vec{q}+\textstyle\sum_{i=1}^{n}\overrightarrow{P^{(i)}}\,\delta(\varepsilon-\varepsilon_i) \tag{6}$$

$$\vec{T}=\ \vec{\mu}+\textstyle\sum_{v=1}^{\rho}\overrightarrow{T^{(v)}}\,\delta(\varepsilon-\varepsilon_v) \tag{7}$$

where:

$\vec{q}$ – vector of distributed force;

$\vec{P}^{(i)}$ – vector of concentrated force;

$\vec{\mu}$ – vector of distributed moment;

$\vec{T}^{(v)}$ – vector of concentrated moment;

$\varepsilon_i$, $\varepsilon_v$ – curvilinear coordinates of the application of the corresponding vectors.

Solution (1) - (5) is implemented by projecting on the axis of the moving coordinate system using the following system of boundary conditions

$$u_1(0)=0,\ u_2(0)=0,\ u_3(0)=0$$
$$\vartheta_1(0)=0,\ \vartheta_2(0)=-\alpha^{0xz}{}_{n(0)},\ \vartheta_3(0)=-\alpha^{0xy}{}_{n(0)}$$
$$Q_1(1)=P^{(1)}{}_1,\ u_2(1)=0,\ u_3(1)=0$$
$$M_1(1)=0,\ M_2(1)=0,\ M_3(1)=0$$

$u_i(\varepsilon)$, $Q_i(\varepsilon)$, $M_i(\varepsilon)$ – projections of the displacement vector, transverse force and bending moment on the axis of the moving coordinate system; *i* = 1, 2, 3.

PU deflection in the vicinity of a given point of inclinometry is determined using the approach described in [14].

## RESULTS OF ANALYTICAL STUDIES OF STRESS-STRAIN STATE OF EQUIPMENT

Using mentioned above methodology, calculations were done. Results are illustrated the position of the points of intersection of the cross-section plane of the well with the PU axis, and for the third version of the design scheme are shown in Fig. 2.

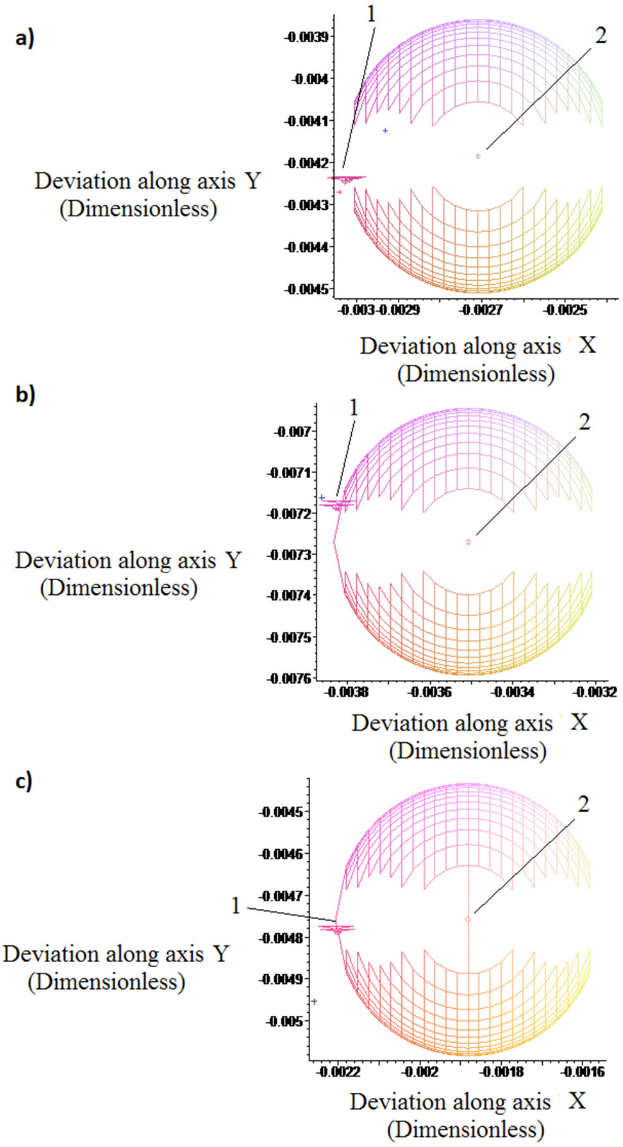

***Fig. 2 – Position of the intersection points of the plane of the well cross section by the PU axis for the third variant of the design scheme***
***a) well cross section at a depth of 1140 m;***
***b) well cross section at a depth of 1150 m;***
***c) cross section of the well at a depth of 1160 m;***
***1 – point of intersection of the plane of the well cross section by the PU axis; 2 – point through which the well axis passes***

Peculiarities of the formation of the PU stress-strain state are reflected in the form of graphs of changes in the normal bending stresses around the main axes of inertia of the cross section (Fig. 3).

Figure 3 shows that maximum bending stresses arise in the upper extreme section of the PU and equal 93 and 45 MPa respectively.

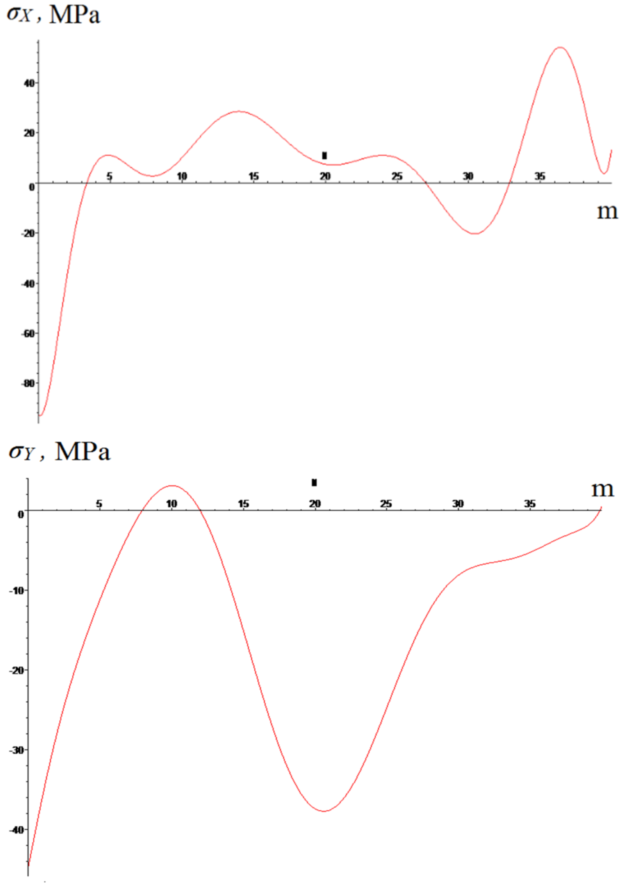

***Fig. 3 Graphs of changes in normal bending stresses around the main axes of inertia of the PU cross section along its length for the third variant of the design scheme***

## RESULTS OF STUDIES OF STRESS-STRAIN STATE OF EQUIPMENT USING THE FINITE ELEMENT METHOD

The analysis of the PU stress-strain state under the same operating conditions is performed using the finite element method in the AnSYS software environment. The following coordinate systems are identified:

1) global coordinate system (GCS 1) – a reference system in which the coordinates of the well inclinometry points are set;
2) local coordinate system (LCS) – a reference system, in relation to which the analysis of the PU stress-strain state model is carried out;
3) global coordinate system of the working environment “AnSYS” (GCS 2) – a reference system, in relation to which a 3D model of the scientific equipment is created in the environment “AnSYS”.

As for analytical studies, according to the third version of the design scheme, the “Z” axis of the LCS passes through the points of the well at a depth of 1130 m and 1170 m. The beginning of the axis is located at a point at a depth of 1130 m, and the orientation of the “X” and “Y” axes is determined according to the technique given in [14].

Based on the calculated dependences given in it, the coordinates of the inclinometry points for the intermediate sections in the LCS are determined (Table 1). They are used in further calculations.

***Table 1***

***Coordinates of the points of the well inclinometry in LCS***

| Point number | Coordinate X, mm | Coordinate Y, mm | Coordinate Z, mm |
|---|---|---|---|
| Point № 1 | -167 | -108 | 9906 |
| Point № 2 | -290 | -140 | 19922 |
| Point № 3 | -190 | -75 | 29963 |

PU 3D model is created in the form of a hollow cylinder (Fig. 4). In this case, the geometric center of the cross section of one of its extreme sections is located at the origin of GCS 2, and the axis of symmetry of the 3D model coincided with the Z axis of GCS 2.

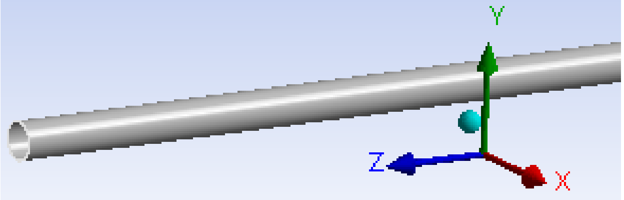

***Fig. 4 PU 3D model***

According to the well-known average value of the moment of inertia for *D* = 121 mm conventional diameter PU the inner diameter d of the equivalent model, 116 mm, is determined.

$$d = \sqrt[4]{D^4 - \frac{64\,I_x}{\pi}} \tag{8}$$

Further modeling is carried out under the condition that LSC coincides with GSC 2. At the first stage of the calculation, it is assumed that the PU axis passes through the points of inclinometry, and its surface does not touch the walls of the well. The deflection of the PU elastic axis, at a distance of 9906, 19922 and 29963 mm from the beginning, is set in the X and Y directions of GSK 2 according to the coordinates given in Table 1. In this case, one of the extreme sections of the model is fixed, with the possibility of changing its linear and angular coordinates, and the movement of another is limited only along the axes "X" and "Y" of GCS 2.

After generating a finite element mesh, reactions in bonds are determined (Table 2).

***Table 2***

***Magnitude of the reactions in the bonds***

| Point number | Reaction parallel to axis X ($R_X$), N | Reaction parallel to axis Y ($R_Y$), N |
|---|---|---|
| Point № 1 | -190 | 140 |
| Point № 2 | -882 | 72 |
| Point № 3 | 209 | 682 |

The obtained results are visualized in Figure 5 as deformations of the PU model.

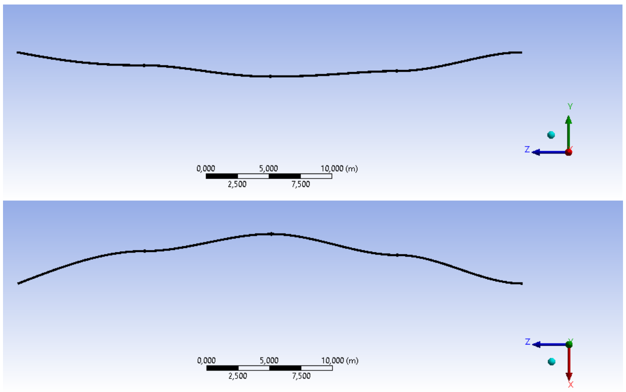

***Fig. 5 Deformation of the PU 3D model***

However, it is quite obvious that the PU axis does not have to pass through the points of inclinometry that lie on the axis of the well. The contact with the walls of the well at certain points is likely. Taking in to account mentioned previously the coordinates of its elastic axis are given as [14].

$$\left(Z, X - \frac{R_X}{\mu_P}, Y - \frac{R_Y}{\mu_P}\right) \tag{9}$$

Moreover, $\mu_P$ is a scale factor and is determined by the formula [14].

$$\mu_P = \frac{\sqrt{R_X^2 + R_Y^2}}{r_{adm}} \tag{10}$$

where:

$r_{adm}$ – admissible deflection of the PU elastic axis equal to the difference between the inner radius of the well and its outer radius.

Subsequently, using the formula (9) and the reaction values are given in Table 2, the true coordinates of the points through which the PU elastic axis will pass take into account the contact between its surface and the borehole walls are determined (Table 3).

***Table 3***

***Coordinates of the points of the PU elastic axis in LSC***

| Point number | Coordinate X, mm | Coordinate Y, mm | Coordinate Z, mm |
|---|---|---|---|
| Point № 1 | -157 | -116 | 9906 |
| Point № 2 | -277 | -141 | 19922 |
| Point № 3 | -194 | -87 | 29963 |

The obtained coordinates are the initial ones for the refinement of the PU stress-strain state.

## DISCUSSION OF RESEARCH RESULTS

To compare the results obtained by the two methods, the third case, the most complicated from a methodological point of view, is subjected to detailed analysis. As can be seen from Figure 3, the maximum stresses from the bending moment arise in the PU initial section and are equal in absolute value of 93 and 45 MPa. Given normal gravity due to their own weight, the normal stresses become 109 and 61 MPa, respectively.

Using the "Probe" function in the AnSYS operating environment, normal bending stresses around the main axes of inertia are determined in the same cross-section of the

PU model. The obtained values are 109 and 90 MPa, respectively. As it is possible to see, there is a satisfactory convergence of the results obtained by two different methods.

Despite the recommendations of the PU manufacturers, to assess the possibility of use in the given conditions, it is sufficient to determine their deflection. For subjects using the proposed methodology in the AnSYS operating environment, objects for determining the deflection of the unit or its individual elements may not pose additional problems. In this case, to increase the accuracy of the assessment of the deformed state, it is necessary to take into account the composition and design features of the PU elements.

## CONCLUSIONS

Based on the results of the analysis of studies of the well profile influence on the operation of pumping equipment and recommendations for ensuring operability, the possibility of its operation in the intervals of the well with different angles of inclination with limited levels of deformation is established. The success of lifting operations and the duration of further operation of the equipment depends on the results of inclinometry and the accuracy of evaluation the influence of the profile of certain intervals of the well on the peculiarities of the PU stress-strain state formation taking into account their design.

To assess the PU stress-strain state in arbitrary intervals of the well with their inclinometry, a new approach is proposed that involves the use of software products based on the finite element method. The sufficient accuracy of the obtained results in this case is confirmed by comparing them with the results of analytical studies performed by a previously tested method. Application of the proposed approach, in the presence of reliable results of inclinometry, will make it possible to assess the level of deformation of individual equipment elements taking into account their design features for comparison with values acceptable by manufacturers.

## REFERENCES

[1] B.S. Aadnoy, M. Fazaelizadeh, and G. Hareland, "A 3D analytical model for wellbore friction," *Journal of Canadian Petroleum Technology*, vol. 49, no. 10, pp. 25-36, 2010. doi: 10.2118/141515-PA.

[2] A. Andrusyak, J. Grydzhuk, A. Dzhus, and I. Steliga, "Developing a method for the assessment of axial load in arbitrary cross-sections of the column of pumping rods," *Eastern-European Journal of Enterprise Technologies*, vol. 1, no. 7, pp. 32-37, 2017. doi:10.15587/1729-4061.2017.92860.

[3] A.V. Degovtsov, T.R. Dolov, S.V. Krivenkov, B.V. Kuznetsov, S.S. Pekin, and A.A. Sabirov, "Determination of Fatigue Strength of Electric Submersible Pumps Shafts," *Territorija «NEFTEGAS» – Oil and Gas Territory*, no. 5, pp. 26-32, 2018.

[4] A.V. Degovtsov, V.N. Ivanovsky, S.V. Krivenkov, I.V. Kuznetsov, A.A. Lavrinenko, A.R. Mukhametshin, and A.A. Sabirov, "Analysis of the causes of fatigue failures of the ESP units shafts," *Equipment and Technologies for Oil and Gas Complex*, no. 2, pp. 27-33, 2018. doi: 10.30713/1999-6934-2018-2-27-33.

[5] A. Dzhus, A. Andrusyak, J. Grydzhuk, and T. Romanyshyn, "Development of the method for estimating serviceability of equipment for the transportation of compressed natural gas," *Eastern-European Journal of Enterprise Technologies*. vol. 4, no. 7, pp. 67-73, 2018. doi: 10.15587/1729-4061.2018.139603.

[6] Z.-M. Feng, J.-J. Tan, Q. Li, and X. Fang, "A review of beam pumping energy-saving technologies," *Journal of Petroleum Exploration and Production Technology*, vol. 8, no. 1, pp. 299-311, 2018. doi: 10.1007/s13202-017-0383-6.

[7] N.M. Ishmurzin, T.N. Khoanh, and R.N. Ponomarev, "About choice of an interval of placing of a pumping unit in the directed wells," *Petroleum Engineering*, no.1, 2006.

[8] V. Kharun, A. Dzhus, I. Gladj, P. Raiter, T. Yatsiv, N. Hedzyk, O. Hryhoruk, and S. Kasatkin, "Improving a technique for the estimation and adjustment of counterbalance of sucker-rod pumping units' drives," *Eastern-European Journal of Enterprise Technologies,* vol. 6, no. 1, pp. 40-46, 2018. doi: 10.15587/1729-4061.2018.150794.

[9] L.-M. Lao and H. Zhou, "Application and effect of buoyancy on sucker rod string dynamics," *Journal of Petroleum Science and Engineering,* vol. 146, pp. 264-271, 2016. doi: 10.1016/j.petrol.2016.04.029.

[10] P.A. Lollback, G.Y. Wang, and S.S. Rahman, "An alternative approach to the analysis of sucker-rod dynamics in vertical and deviated wells," *Journal of Petroleum Science and Engineering*, no. 17 (3-4), pp. 313-320, 1997. doi: 10.1016/S0920-4105(96)00070-8.

[11] Q. Li, B. Chen, Z. Huang, H. Tang, G. Li, and L. He, "Study on Equivalent Viscous Damping Coefficient of Sucker Rod Based on the Principle of Equal Friction Loss," *Mathematical Problems in Engineering*, vol. 2019, 2019. doi: 10.1155/2019/9272751.

[12] R.N. Ponomarev and N.M. Ishmurzina, "Research of density of emergency refusals of affected by the operating time of diving centrifugal pumps installations of centrifugal from their operating time," *Petroleum Engineering*, vol. 4, no.1, pp. 221-224, 2006.

[13] R.N. Ponomarev and N.M. Ishmurzin, "Analysis of emergency failures due to construction of wells and electric centered pump installations," *Petroleum Engineering*, no. 2, 2006.

[14] R. Rachkevych, "Application of rod mechanics fundamentals for analysis of stress-strain state of the tubing," *Technology Audit And Production Reserves*, vol. 5, no. 1(31), pp. 35-44, 2016. doi: 10.15587/2312-8372.2016.79609.

[15] A. Sikal, J. Boulet, S. Menand, and H. Sellami, "Drill Pipe Stress and Cumulative Fatigue Analysis in Complex Wells Drilling: New Approach in Fatigue Optimization". *2008 SPE Annual Technical Conference and Exhibition held*. (Denver, 21-24 Sept. 2008), Denver, pp. 1-17, 2008.

[16] V.A. Svetlitskyi, *Mechanics of rods: Tutorial for high school. Part 1. Static*. Moscow, 1987.

[17] A. Velychkovych, I. Petryk, and L. Ropyak, "Analytical Study of Operational Properties of a Plate Shock Absorber of a Sucker-Rod String," *Shock and Vibration*, vol. 2020, article ID 3292713, 2020. doi: 10.1155/2020/3292713.

[18] D.-Y. Wang and H.-Z. Liu, "Dynamic modeling and analysis of sucker rod pumping system in a directional well," *Lecture Notes in Electrical Engineering*, vol. 408, pp. 1115-1127, 2017. doi: 10.1007/978-981-10-2875-5_90.

[19] A. Wu, G. Hareland, and M. Fazaelizadeh, "Torgue and Drag Analysis Using Finite Elements Method," *Modern Applied Science,* vol. 5, no. 6, pp. 13-27, 2011.

[20] M. Xing and S. Dong, "An improved longitudinal vibration model and dynamic characteristic of sucker rod string," *Journal of Vibroengineering*, vol. 16, no. 7, pp. 3432-3448, 2014.

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