UDC 621.644.074
DOI: 10.15587/2706-5448.2025.336165

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JUSTIFICATION OF THE METHODOLOGY FOR INSTALLING A DEFORMATION RECORDER IN A MAIN PIPELINE SECTION THROUGH ANALYSIS OF ITS STRESS-STRAIN STATE

Object of the research is a deformation recorder designed for monitoring the stress-strain state of main pipelines. This study investigates the hypothesis regarding the feasibility of installing a deformation recorder on a pipeline section that has been preloaded with the maximum allowable operating pressure, in order to ensure the recorder's reliable performance under various pipeline operating conditions. Structurally, the examined deformation recorder consists of two clamps, with four longitudinal strain multipliers mounted at diametrically opposite locations between them. By comparing their relative strain values, it is possible to determine the spatial curvature of the pipeline axis. A 3D model of a pipeline section with a diameter of 270 mm and wall thickness of 5 mm was developed, incorporating a deformation recorder with a measurement base of 300 mm. Based on this model, a multi-step finite element model was created to calculate the stress-strain state and the contact interaction of a 4.6-meter-long pipeline section. One end of the pipeline was modeled as axially compliant, and the stress recorder was installed on it. Series of numerical experiments were conducted to analyze the stress-strain behavior of the assembly under varying preload forces of the clamp bolts. The results confirmed the initial hypothesis and allowed the determination of an acceptable preload range. Specifically, the preload force must be no less than 15 kN to ensure secure attachment of the clamps on a non-operational pipeline, and must not exceed 30 kN to comply with the pipeline's strength requirements. Based on the analysis, recommendations were made regarding the development of a redesigned clamp lock. Additionally, the study proposes that changing the material of the deformation recorder may reduce the required bolt preload force.

Keywords: *main oil and gas pipeline, stress-strain state, express analysis, deformation recorder.*

*Received: 26.03.2025
Received in revised form: 02.07.2025
Accepted: 23.07.2025
Published: 30.08.2025*

How to cite

Slabyi, O., Shlapak, L., Grydzhuk, Ya., Deineha, R., Popovych, V. (2025). Justification of the methodology for installing a deformation recorder in a main pipeline section through analysis of its stress-strain state. Technology Audit and Production Reserves, 4 (1 (84)), 6–11. https://doi.org/10.15587/2706-5448.2025.336165

1. Introduction

Main oil and gas pipelines play a critical role in the transportation of energy resources, ensuring the uninterrupted delivery of liquid and gaseous fuels from extraction sites to end users. These pipelines constitute a complex network laid across diverse geological and engineering conditions, designed for long-term operation and subjected during use to a complex stress-strain state. To ensure accident-free operation, pipeline loads must remain within allowable stress limits.

Assessment of a pipeline's stress-strain state is complicated by the influence of both anticipated operational loads and unforeseen external factors, such as soil displacements, subsidence, localized erosion of supports, and ground washouts caused by heavy rainfall, floods, or other hydrological events. In this context, it is advisable for operating companies to implement rapid assessment systems for monitoring the stress-strain state in potentially hazardous pipeline sections to prevent the occurrence of emergency situations. This study is devoted to analyzing the performance and fastening features of one such monitoring system.

Industrial pipeline operation data show that soil displacement significantly affects the pipeline's stress-strain behavior, potentially leading to critical stress levels and eventual structural failure, posing serious safety hazards [1–3]. Numerous analytical and experimental studies of pipelines with various structural designs support this finding [2–5], highlighting the need for continuous monitoring of stress-strain conditions in critical pipeline segments to ensure reliable and safe operation.

To date, a variety of stress-strain monitoring methods for main pipeline sections have been developed, based on different physical principles. In [6], for instance, it is proposed to assess the stress-strain state of a pipeline laid in a landslide-prone area by analyzing variations in the natural impulse electromagnetic field. This approach enables the evaluation of rock mass stress states and, consequently, their effect on the pipeline.

Another method for assessing pipeline integrity is described in [7], where stress sensors are mounted on the pipeline and are designed to fail when stresses exceed a defined threshold. Visual inspection of these sensors helps to identify localized high-stress zones, which are then assessed using a device based on the magnetoelastic effect in ferromagnetic materials. The advantage of this two-stage analysis is a reduction in the number of measurements required to locate stress peaks.

In [8], a comprehensive multi-step methodology is proposed, which includes the identification of landslide-prone areas, continuous monitoring, and prediction of landslide evolution, leading to the identification of optimal locations for strain gauge monitoring posts along the pipeline.

A common drawback of directly attaching strain gauges to pipeline walls is the complexity of interpreting the data and the high sensitivity to external disturbances, which can significantly affect measurement accuracy. To address these issues, a new method for stress-strain monitoring was proposed by the authors in [9, 10], which involves the mechanical installation of a specially designed deformation recorder on the pipeline. This recorder allows for independent measurement of both circumferential and longitudinal relative strains using pre-calibrated laboratory strain gauges mounted on the device.

This solution offers several advantages: it eliminates the need for welding during installation, provides a relatively large deformation measurement base (minimizing the effect of local variations in mechanical properties), and improves measurement accuracy through laboratory pre-calibration. However, the practical validation of these concepts still requires further analytical and experimental investigation.

Thus, *the aim of this research* is to verify the operational capability of the proposed deformation recorder for main pipelines under all working conditions by numerically simulating its stress-strain behavior.

2. Materials and Methods

2.1. Object and hypothesis of the research

The object of this research is a deformation recorder designed for monitoring the stress-strain state of main pipelines [9]. The developed device is intended to support rapid decision-making regarding whether to continue operation or shut down an oil or gas pipeline for maintenance in the event of unforeseen changes in loading at segments with curvature. The basic structure of the deformation recorder is shown in Fig. 1. It consists of two clamps 1, which are mounted onto the pipeline and secured using bolts 3. Between the clamps, four specially designed plates 4 are installed at diametrically opposite positions; these act as longitudinal strain multipliers. The plates 4 may also serve as safety elements by failing when critical strain levels are reached in the pipeline. Strain gauges for measuring longitudinal 5 and circumferential 6 strains are mounted at designated positions on the recorder. By analyzing the differences in the longitudinal strain gauge readings 5, and accounting for the circumferential deformations measured by gauges 6, it becomes possible to assess the local deformation of the pipeline axis and, accordingly, evaluate its three-dimensional stress-strain state.According to the authors, the proposed design of the deformation recorder offers several advantages:

- convenient and rapid installation;
- sufficiently large base length for longitudinal strain measurements, reducing the influence of local anomalies;
- independent measurement of circumferential and longitudinal deformations;
- the possibility of pre-calibrating the device under laboratory conditions [10].

The structural design of the deformation recorder assumes that the clamps 1 and strain multipliers 4 must remain pre-tensioned during operation to ensure the accuracy of the data from the strain gauges.

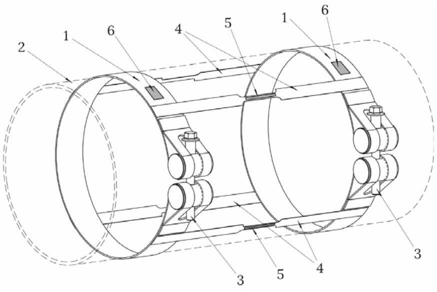


Fig. 1. Design of the deformation recorder: 1 – clamp; 2 – pipeline; 3 – installation bolt; 4 – deformation multipliers; 5 – longitudinal strain gauges; 6 – circumferential strain gauges

A key feature of a pipeline's stress-strain behavior is that with increasing internal pressure, the pipeline's radial dimension increases while the axial length decreases. Therefore, if the deformation recorder is installed when the pipeline is not pressurized, the transition to operational pressure will cause axial shortening of the pipeline due to radial deformation. This leads to compression of the strain multipliers, potentially impairing their performance.

Based on this, the authors propose the hypothesis that it is possible to ensure consistent tension in the strain multipliers across different operating conditions – without requiring additional equipment during installation – if the recorder is installed when the pipeline is pressurized to a level equal to or greater than its maximum operating pressure. Such conditions can be achieved, for instance, during pipeline pressure testing. In this scenario, the axial shortening of the pipeline is at its maximum, and if the working pressure during operation does not exceed the pressure during recorder installation, the multipliers will remain pre-tensioned (assuming the clamps do not slip along the pipeline) and function correctly. To prevent slippage, the bolt preload at the time of clamp installation must be sufficient to keep the clamps securely pressed against the pipeline surface even when there is no internal pressure (and thus no radial deformation).

2.2. Selection of research method and model development

After analyzing existing approaches, the chosen method for this study involves creating a three-dimensional model of the stress recorder mounted on a pipeline section and, based on it, constructing a multistep finite element model (FEM). The developed model serves as the basis for a series of numerical experiments under varying attachment conditions of the stress recorder to assess the stress-strain state of the pipeline section with the installed device. The results will be used to evaluate the functionality of the deformation recorder, formulate methodological recommendations for its installation, and provide guidance for future studies.

The object of the study is a deformation recorder mounted on a section of main pipeline with a diameter of 270 mm and a wall thickness of 5 mm. The gauge base of the recorder is 300 mm, and its main geometric dimensions are shown in Fig. 2. The thickness of the deformation multipliers is set at 0.5 mm.

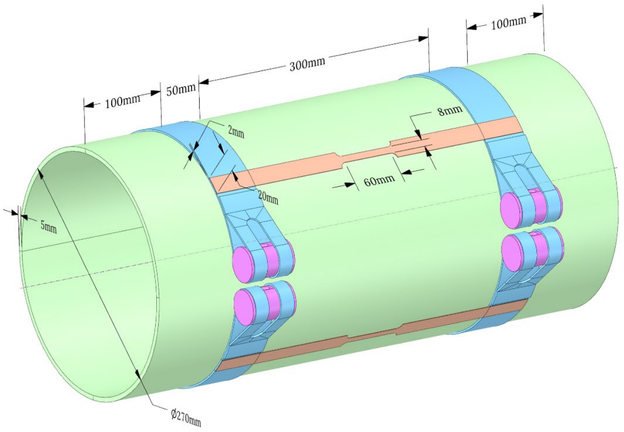


Fig. 2. Main geometric dimensions of the investigated model

Based on the developed 3D model, a finite element model of the investigated object was constructed, with the mesh shown in Fig. 3. Considering that the objective is to analyze the stress-strain state of the pipeline 6, clamps 1 and 2, and deformation multipliers 5, the following modeling assumptions were applied (Fig. 3):

1. To reduce the mathematical complexity, the clamp lock axes 3 are modeled as rigid bodies, and the bolts 4 are modeled as beam elements with a diameter of 12 mm.

2. The contact surfaces between the clamps 1 and 2 and the pipeline 6 are modeled as frictional contacts, allowing for separation.

3. The contact zones between the deformation multipliers 5 and the clamps 1 and 2 are modeled as bonded.

4. The contacts between the lock axes 3 and the clamp loops are modeled as no-separation contacts.

5. To ensure high mesh quality, the clamps 1 and 2 and deformation multipliers 5 were split into segments and then joined using bonded contacts.

6. The pipeline section 6, clamps 1 and 2, and deformation multipliers 5 are represented using hexahedral (Hexa) elements with four layers through the thickness of each body.

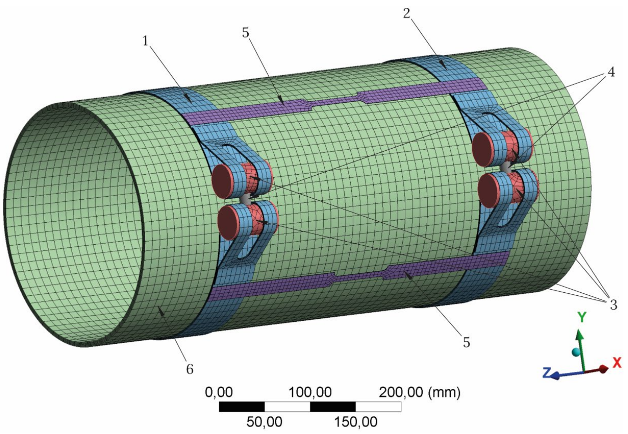


Fig. 3. Finite element model of the investigated object: 1, 2 – clamps; 3 – lock axis; 4 – installation bolt; 5 – deformation multipliers

As a result, the finite element model contains 32,613 elements, 166,045 nodes, 39 solid bodies, and 77 contact surfaces. All deformable components are modeled using structural steel. Friction between the clamps and the pipeline is defined according to the Amontons-Coulomb law, with a friction coefficient of 0.4, accounting for the typically rough surface condition of pipelines.

To solve the model, appropriate boundary conditions and external loads were applied, based on the task of evaluating the stress-strain state of the pipeline section during deformation recorder installation. The following conditions are imposed (Fig. 4):

1. The inner surface of the pipeline (zone A) is subjected to internal pressure acting normal to the surface, representing the transported medium.

2. Preload forces are applied to the beam elements B and C, representing the bolts.

3. *Remote Displacement* boundary condition is applied at the pipeline end, constraining a point located 2 meters from the end (not shown to scale in Fig. 4). At point D, all degrees of freedom are restricted, while at point E, only displacement along the *X* and *Y* axes and rotation about the *Z* axis are constrained (Behavior: flexible).

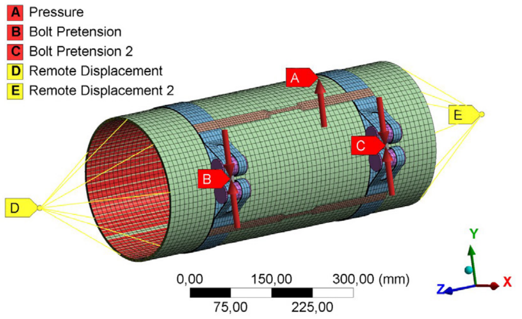


Fig. 4. Applied loads and boundary conditions of the finite element model

All other external loads acting on the pipeline section are considered negligible and thus omitted. The final model allows for simulating the stress-strain behavior of a 4.6-meter pipeline section with an installed deformation recorder, one end of which remains axially compliant. This boundary condition setup enables simulation of the most challenging operating scenario-axial compliance of the pipeline due to its radial deformation under internal pressure from the transported medium.

2.3. Defining the installation sequence of the deformation recorder in the model

Based on the proposed hypothesis regarding the installation of the deformation recorder, the task of studying the variation in the stress-strain state of the system during the mounting process was solved in four steps:

1. *Step 1*: A pressure of 6 MPa – corresponding to the maximum operating pressure of the pipeline – was applied to the internal surface of the pipeline. The status of the clamp bolt connections was set to open, allowing the beam elements (representing the bolts) to deform freely without generating reaction forces.

2. *Step 2*: The installation of the first clamp was modeled by applying a predefined bolt pretension force (status: load) to the corresponding connection. The internal pressure in the pipeline remained at 6 MPa, and the second clamp's bolt remained in the open state.

3. *Step 3*: The installation of the second clamp was modeled by applying a bolt pretension force (status: load) to its connection. The internal pressure remained at 6 MPa. At this stage, the first clamp's bolt connection was set to lock, preserving the deformation of the beam element (bolt) obtained in the previous step.

4. *Step 4*: The pipeline was depressurized to evaluate the reliability of the clamp fixation and the potential for slippage. The internal pressure was reduced to zero, and the status of both bolt connections was set to lock.

The use of this multi-step modeling procedure enables the evaluation of how the stress-strain state of the pipeline section changes during installation of the deformation recorder, and allows for verification of the recorder's operational reliability and clamp retention quality under the full range of operating conditions.

A series of numerical experiments was conducted using this model, with various values of bolt pretension forces applied to the clamp fasteners.

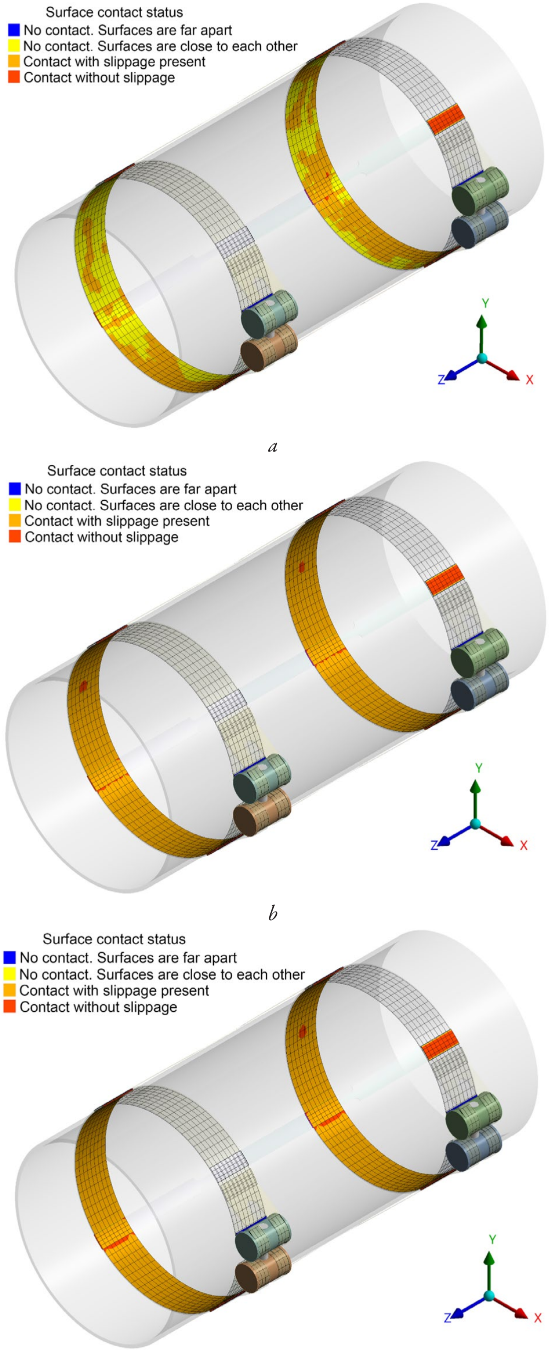
3. Results and Discussion

The conducted investigation into the stress-strain state of a pipeline section with an installed deformation recorder demonstrates that radial deformation caused by internal pressure variation is a critical factor influencing the quality of the clamp-to-pipeline interface. Fig. 5 presents a graphical representation of the clamp-to-pipeline contact under different bolt pretension forces.

As seen, a pretension force of 10 kN is insufficient to ensure reliable contact – when internal pressure is reduced, the clamps detach from the pipeline wall. At pretension forces of 15 and 20 kN, the clamp surfaces – except for small areas near the locking loop – remain in contact with the pipeline, though some circumferential slippage of the clamps is observed. Specifically, circumferential displacement up to 0.5 mm at 30 kN and 0.31 mm at 15 kN was recorded. This is attributed to redistribution of forces within the clamps due to pipeline radial deformation.

A negative effect of this phenomenon is that the presence of slippage significantly reduces the friction force between the clamp and the pipeline, and thus, in the case of pipeline curvature, it may also lead to axial displacement of the clamps. However, this issue requires further investigation considering the dynamics of frictional interaction. The obtained data show that, for reliable attachment of the deformation recorder, the bolts must be pretensioned with a force exceeding 15 kN.

Although this pretension force is within the working range for M12 bolts of strength class 12.9, it causes critical stresses in the clamp lock loops. Therefore, in order to ensure high-quality clamp fastening, a new lock design should be developed. Other ways to reduce the required bolt pretension force include the use of adhesives during installation and the fabrication of clamps from materials with a significantly lower Young's modulus. This should ensure the required clamp deformation to compensate for pipeline radial deformation and maintain continuous contact with the pipeline at significantly lower bolt pretension forces.



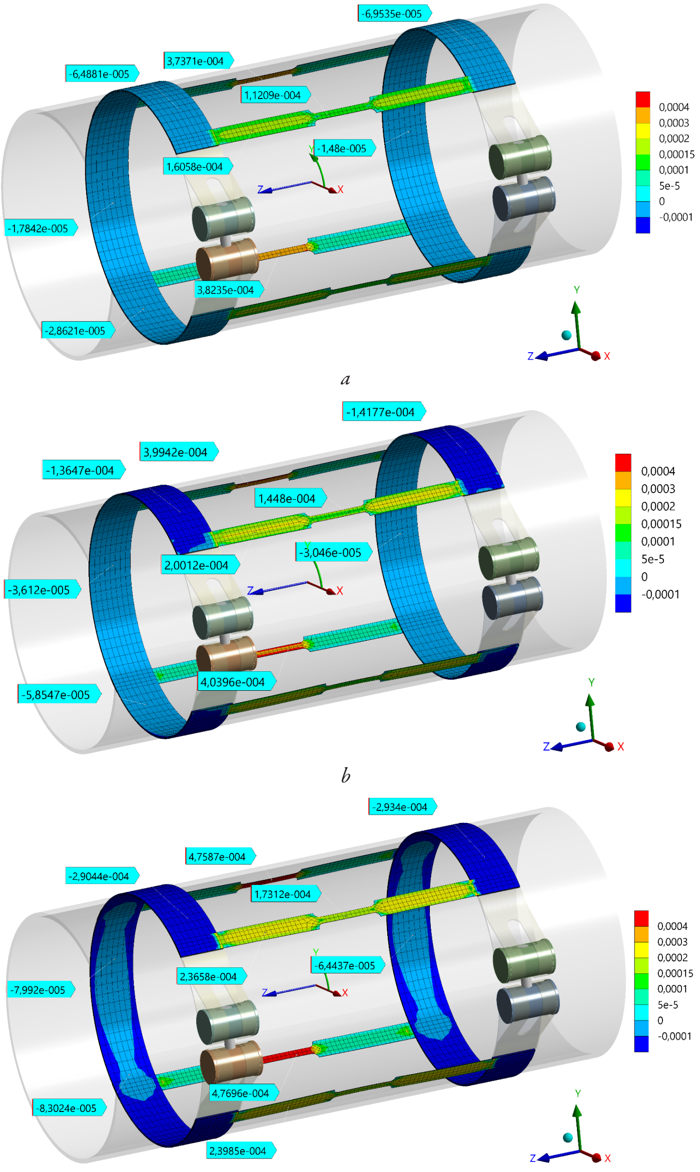
a

b

c

Fig. 5. Clamp-to-pipeline contact status under zero internal pressure and varying bolt pretension forces: *a* – 10 kN; *b* – 15 kN; *c* – 20 kN

Fig. 6 presents the graphical representation of the distribution of relative axial strains in the elements of the deformation recorder under different bolt pretension forces. The obtained results confirm the hypothesis regarding the advisability of installing the deformation recorder on a pressurized pipeline. After pressure release, the strain multipliers remain in a tensioned state. However, simulation results show that the highest relative linear deformations occur on the "inner" side of the deformation multipliers, and their magnitude is 2–3 times greater than that on the opposite "outer" side. Based on this, it is advisable to install strain gauges on the inner side of the deformation multiplier.



a

b

c

Fig. 6. Distribution of relative axial strain in the stress recorder after pressure release at various bolt pretension forces: *a* – 15 kN; *b* – 20 kN; *c* – 30 kN

The relatively small variation in linear elongation of the deformation multipliers depending on the bolt pretension force can be explained by the complex spatial stress-strain state of the clamps due to residual circumferential tension. As a result, the clamp width decreases, which in turn affects the longitudinal deformation of the multipliers. The influence of this effect on the measurement error of axial strain can be programmatically compensated by knowing the magnitude of the circumferential tension in the clamp, which can be measured using a strain gauge mounted on the clamp (pos. 6 in Fig. 1). Analysis of relative circumferential linear deformations in the clamp body shows a linear increase from the center of the clamp to its ends, where the lock loops are located. This can be explained by the influence of friction forces that resist circumferential movement of the clamp. Considering this, the strain gauge (pos. 6 in Fig. 1) used to determine circumferential stress in the clamp should preferably be placed at a point diametrically opposite the lock.

The need to apply significant pretension forces to the installation bolts to reliably secure the recorder leads to a significant change in the stress distribution in th e pipeline section where the recorder is mounted. Fig. 7 presents a graphical representation of the equivalent stress distribution (according to the von Mises yield criterion) in the investigated object at different bolt pretension forces. As can be seen, the pipeline section where the deformation recorder is mounted is in a rather complex and non-uniform stress state. The observed stress magnitude directly depends on the bolt pretension force. For example, with a pretension of 15 kN, pipeline stresses range from 30 to 200 MPa; at 20 kN, from 20 to 230 MPa; and at 30 kN, from 6 to 350 MPa, while for a pipeline without a recorder, they range from 150 to 165 MPa. It should be noted that the maximum stress values in the pipeline with a recorder installed at 30 kN pretension are comparable to the yield strength (355–390 MPa) of steels 17G1S and 09G2S, which are used for main pipelines. Therefore, the 30 kN bolt pretension force can be considered the maximum allowable for this recorder. The presence of localized stress concentration zones under the clamp locks suggests that one way to reduce them is by developing a new clamp lock design. The appearance of weakly loaded zones on the side of the clamp locks may be explained by clamp slippage during installation. Their magnitude depends on the friction force between the clamp and the pipeline. Since predicting the actual friction force is difficult, this should be taken into account in the form of a safety factor when determining the maximum allowable bolt pretension force.

One method for approximate estimation of friction forces between the clamp and the pipeline is to measure the change in circumferential stress along the clamp using strain gauges. Another way to reduce the clamp's influence on circumferential stress distribution in the upper layers of the pipeline is to use a clamp with multiple locking points.

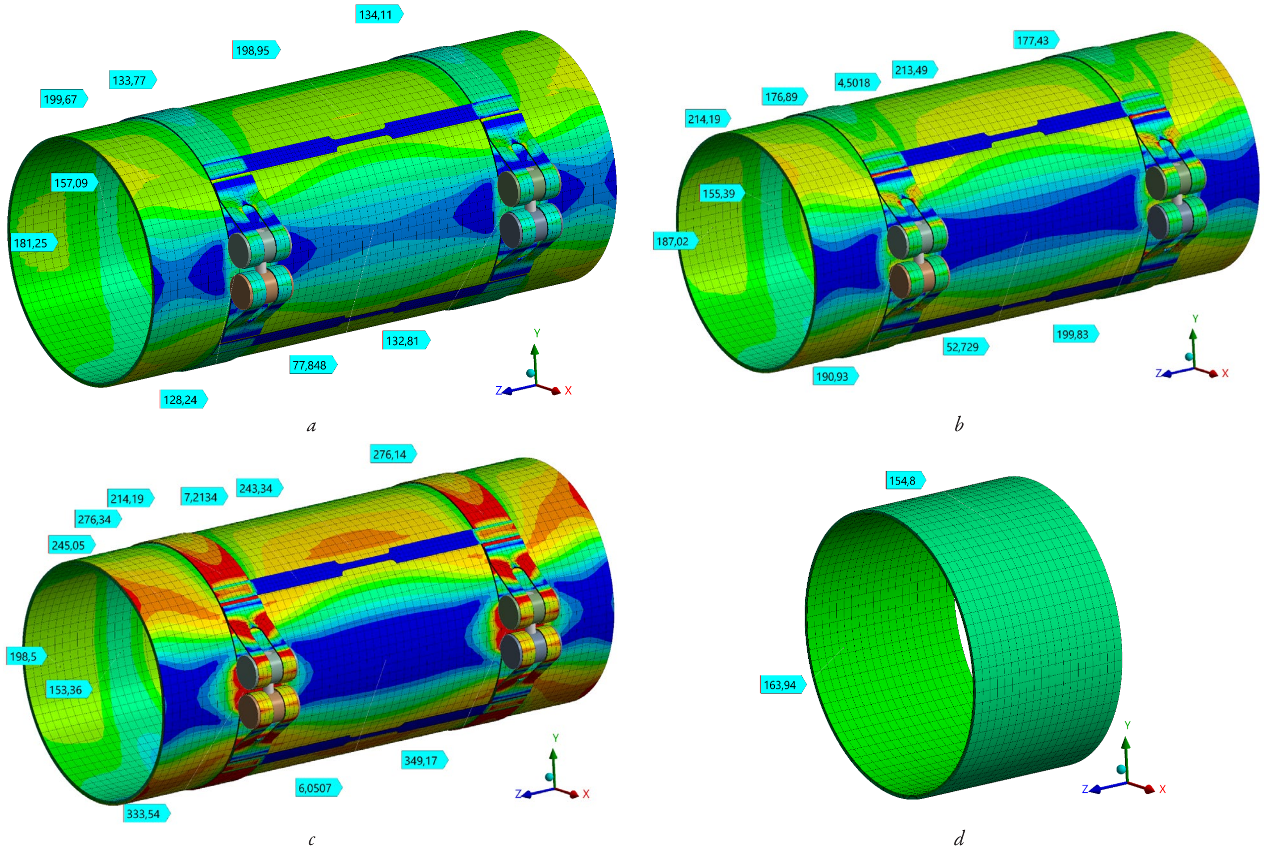
In general, the results of the numerical experiments confirmed the viability of using deformation recorders of the proposed design in systems for monitoring the technical condition of main pipelines. It was established that there is a sufficiently wide range of bolt pretension forces for which the device remains functional under all pipeline operating modes.

A limitation of this study is that only a single case of the stress-strain state of the pipeline section during recorder installation and normal operating conditions, without axial pipeline deformation, was considered. For complete validation of the device's performance, it is also necessary to investigate the stress-strain behavior of the pipeline section with the installed recorder under axial deformation caused by external forces and to conduct full-scale field tests.

4. Conclusions

The study validated the hypothesis regarding the advisability of installing a deformation recorder on a main pipeline section pressurized to its maximum allowable operating pressure. This approach was intended to ensure the recorder's operability under all pipeline operating conditions.

To that end, a finite element model was developed for a deformation recorder with a gauge base of 300 mm, mounted on a pipeline section with a diameter of 270 mm and a wall thickness of 5 mm. The model enables analysis of the contact interaction between the deformation recorder and the pipeline, as well as their stress-strain state under varying internal pressures and clamp bolt pretension forces.



a *b* *c* *d*

Fig. 7. Equivalent stress distribution (von Mises criterion) at 6 MPa internal pressure and different bolt pretension forces: *a* – 15 kN; *b* – 20 kN; *c* – 30 kN; *d* – stress distribution in the unloaded pipeline (for comparison)

The results of numerical experiments confirmed the proposed hypothesis. An acceptable range of bolt pretension forces was also determined, based on the conditions for maintaining continuous clamp-to-pipeline contact and limiting maximum allowable stresses in the pipeline material. For the system under study, this range was established at 15–30 kN.

The results obtained in this work confirm the viability of using mechanically mounted deformation recorders for monitoring the deformation of the pipeline axis in high-risk segments. The developed finite element model can also be used for future studies of other operating scenarios, and its results may be applied in the development of microcontroller software for pipeline deformation monitoring systems.

Conflict of interest

The authors declare that they have no conflict of interest related to this study, including financial, personal, authorship-related, or other factors that could have influenced the research or its results as presented in this article.

Financing

This research was conducted without financial support.

Data availability

Data will be made available upon reasonable request.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

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