doi: 10.18720/MCE.80.3

Influence of the compensating device parameters on the underwater pipeline stability

Влияние параметров компенсирующего устройства на устойчивость подводного трубопровода

K.V. Kozhaeva,
Ufa State Petroleum Technological University, Ufa, Russia

Канд. техн. наук, старший преподаватель К.В. Кожаева,
Уфимский государственный нефтяной технический университет, Уфа, Россия

Key words: experiment; compensating device; rational parameters; correction coefficient of the compensator form; ensuring the pipeline stability

Ключевые слова: эксперимент; компенсирующее устройство; рациональные параметры; коэффициент уточнения формы компенсатора; обеспечение устойчивости трубопровода

Abstract. The definition of rational parameters of the developed compensating device of a triangular shape by calculation and experimental investigation methods is considered in the article. The proposed compensating device with the bent taps use has a more rigid design than the compensating device in the form of a broken bolt. Consequently, the correction coefficient of the compensator form, structurally executed with the use of bent taps is received by calculation and experimental methods for decreasing the longitudinal compressive force arising from the temperature drop to the ensuring level of the overall pipeline stability in the longitudinal direction, which allows to determine its rational parameters and is taken to be k = 0.85. The condition is obtained for determining the rational parameters of the proposed compensating device for underwater pipeline transitions in order to increase the overall stability in the longitudinal direction. In addition, the patented technology of laying the proposed compensating device is shown.

Аннотация. В статье рассматривается определение рациональных параметров разработанного компенсирующего устройства треугольной формы с помощью расчетно-экспериментальных методов исследования. Предлагаемое компенсирующее устройство с применением гнутых отводов обладает более жесткой конструкцией, чем компенсирующее устройство в виде ломаного ригеля. Поэтому расчетно-экспериментальным методом получен коэффициент уточнения формы компенсатора, конструктивно выполненного с применением гнутых отводов, для снижения продольного сжимающего усилия, возникающего от температурного перепада, до уровня обеспечения общей устойчивости трубопровода в продольном направлении, который позволяет определить его рациональные параметры, и принимается равным k = 0,85. Получено условие для определения рациональных параметров предлагаемого компенсирующего устройства для подводных переходов трубопроводов с целью повышения общей устойчивости в продольном направлении. Также приведена запатентованная технология укладки предлагаемого компенсирующего устройства.

1. Introduction

The stabilization loss of the underwater pipelines sections position leads to emergencies and the removal of the pipeline from service. In most cases, the stabilization loss of the pipeline (including arched emissions) occurs due to the action of compressive longitudinal forces, which must be prevented or reduced [1–7].

The analysis of foreign works devoted to ensuring the stability and reliability of pipelines, including submarine ones, prove the relevance of the solved problems not only in Russia [8–21].

In the Russian regulatory documents, the calculation of the underwater pipeline for longitudinal stability is not carried out, albeit these calculations are needed abroad. This fact is confirmed also by the authors of the works [22, 23]. Indeed, at present time, most underwater pipelines operate at significant positive temperature changes, which causes large compressive longitudinal forces that can lead to the pipeline from a stable state. In the work [23], the authors focus on the calculation of the operational reliability of a gas underwater pipeline in which a loss of longitudinal stability occurred. This is very important, since the pipeline, which lost its longitudinal stability, is primarily susceptible to destruction. The following issues are considered in detail in the article:

– who dealt with the issues of ensuring the longitudinal stability of pipelines;
– what methods determine the critical longitudinal force and possible loss forms of the pipeline stability;
– a comprehensive assessment of the technical condition of the gas pipeline sections based on numerical methods;
– reliability analysis of underwater pipelines based on traditional methods of structural mechanics, as well as the finite element method;
– assessment of the pipeline reliability with arched ejection under the random weight load influence from the backfill ground, as well as random operational loads, using the probabilistic estimation method.

The methods of ensuring the spatial gas pipeline stability on the watered sections of the route were considered in detail in [24, 25], taking into account the influence of variable ground conditions (water saturation, ultimate shear resistance and cohesion). The authors considered the gas pipeline section on which the design position loss of the pipeline in the arch form due to high water and also the temperature increase of the transported product - gas. According to the approach proposed by the authors, the main provisions of the methodology and the procedure for calculating additional ballasting of the adjacent areas were developed. As a result, there is a reduction in possible displacements in the central region. The proposed methodology is applicable both in the operation period and in major overhaul of pipelines and for newly laid gas pipelines. Calculation of this method on real objects showed the decrease in the final longitudinal force at the beginning of the adjoined section with additional ballasting in 2,625 times (from 0.42 MN to 0.16 MN). Thereby ballasting of adjoined section reduces the ultimate longitudinal force effect due to the temperature expansion of the pipeline material in the central region and therefore ensures the design position stability of this main gas pipeline section.

However, such pipelines ballasting can lead to additional large costs. Therefore, there is a need to look for an alternative way with minimum costs and maximum reliability. Consider the same adjoined area, but instead of ballasting, it will be equipped with a compensator. There are divergent views and evidence in that regard. In the article [26], the authors considered the stress-strain state modeling of the underground pipelines sections, which consist of a concave or convex insert curve with a curved hollow rod in an elastic medium. The calculations made by the authors confirm the conclusions of the accidents acts that the insert curves are stress concentrators in the gas pipeline. Calculations also allow identifying the physical picture of the insert curve deformation at the stresses concentration in it and highlighting its main parameters, by increasing the insertion curve length and reducing its curvature, the insert will be experienced excessively large bending deformations in the restrained part.

In the articles [27, 28], it was considered how the moist ground degree of adjoined underground areas will affect the underwater gas pipelines stress-strain state. The authors made the following conclusions: when calculating underwater sections of a gas pipeline and also strength and stability evaluating, it is necessary to take into account the internal working pressure effect, the temperature stresses on the pipeline bend and the grounds condition, which adjoin the regions with their properties changes within one year. When constructing subsea gas pipelines, it is necessary to provide for the compensator installation at one end of the underwater transition in the soil of the adjoined regions. In order to reduce the resistance of the pipe movement principle, it is necessary to fill the underground compensators with a soft loosened soil during their laying in mineral grounds. Since the defective properties of the moist ground covers are high, in the flood period the compensator stabilizes the pipeline location and ensures its durability, stability and reliability in operation.

Thereby, it is possible to provide a general stability in the longitudinal direction of the underwater pipeline transition with the compensator installed on an adjoined area to the underwater transition region. As such a design, there is a compensating device for a pipeline, which the calculations and experimental studies are given below [29, 30].

2. Methods

2.1. The experiment planning and modeling

To increase the overall the pipeline stability in the longitudinal direction, it is proposed to reduce the equivalent axial compressive force by installation a compensating device on the adjoined section of the underwater pipeline.

The solution of the problem is to determine the rational compensator parameters with reduction the longitudinal compressive force to a safe level at a specified N_{cr}, an internal pressure p and temperature difference Δt.

The most appropriate for the underwater main pipeline section is the triangular shape of the compensating device, where the straight parts connection of the compensator are carried out by cold bending diversions ensuring the transition of inside pipe devices and instruments.

The trench for laying the compensator should be prepared taking into account the free compensator movement and then backfilling features, thereby reducing the longitudinal force (Figure 1).

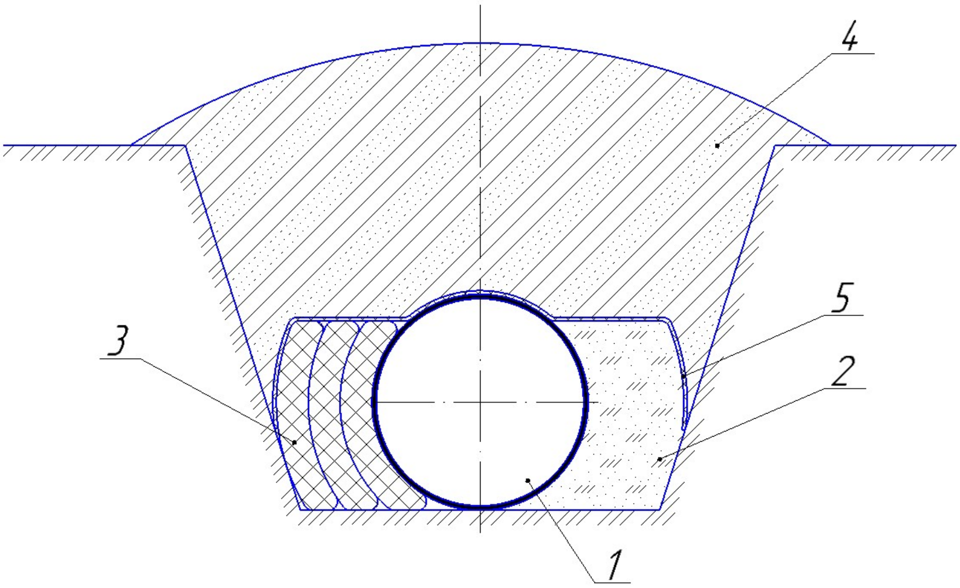

Figure 1. Preparation features and trenches backfilling with the compensator:
1 – compensator; 2 – elastic strain ground; 3 – elastic strain parts; 4 – mineral ground back-filling; 5 – cushioning material

The free pipeline movement into the trench and the natural longitudinal movement compensation of the compensator 1 occur after elastic strain ground 2 back-filling or elastic strain parts 3 installation. It is also necessary to lay the cushioning material 5 along the entire length of the compensator 1 to prevent the mineral ground back-filling 4 between the elastic strain parts 3 or mixing the mineral ground back-filling 4 and the elastic strain ground 2. The cushioning material 5 is a polymeric tape (for example, rubber, polyethylene, polypropylene, polyvinyl chloride), recycled metal cord conveyor belt. The remaining trench volume covers by the mineral ground back-filling 4.

The elastic strain parts 3 are bags or containers of various geometric shapes and sizes depending on the pipeline diameter and the construction area filled with chips of non-pressed fiberglass materials or foam propylene, foam and other elastic strain materials that withstand up to 2 t/m^2 of ground with deformation up to 5–10% from the maximum deformation potential. A peat can be used as an elastic strain ground.

According to the Figure 2, longitudinal compressive force quantity S in the underwater transition will depend on the compensator parameters: length l и deflection f.

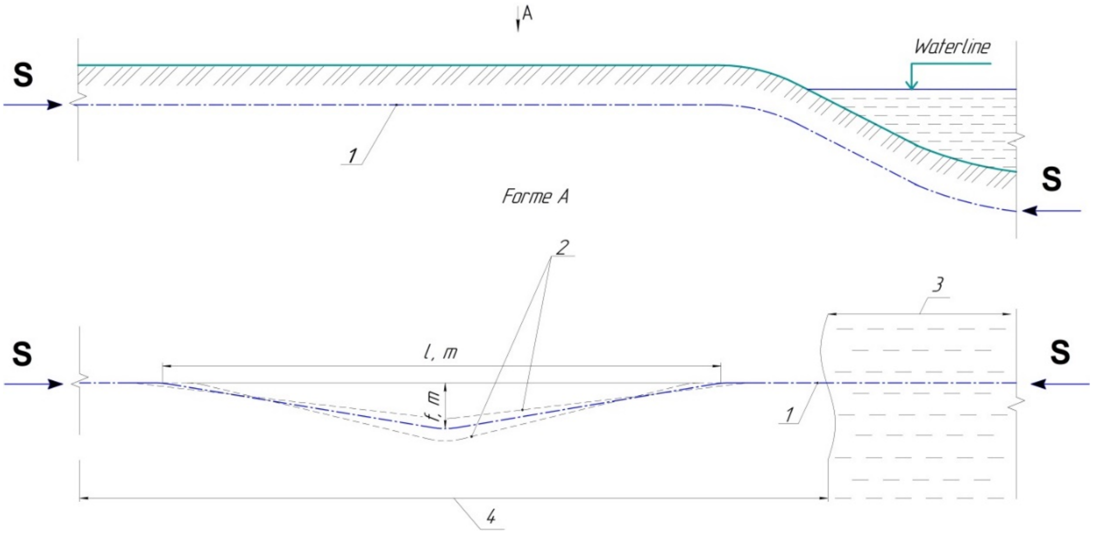

Figure 2. Underwater pipeline transition with a compensating device on an adjoined area: 1 – pipeline axis; 2 – possible compensator axis movements; 3 – underwater area; 4 – the adjoined compensator area of a triangular shape

The selection of the compensator parameters in the form of "snake" (Figure 3) and their calculation are considered in detail in [31]. The value of the equivalent longitudinal axial force S taking into account the longitudinal displacements compensation caused by the temperature change the pipe walls and internal pressure is determined by the formula (1):

$$S = \frac{3 \cdot cos\varphi \cdot I \cdot (\alpha \cdot E \cdot \Delta t + 0{,}2 \cdot \sigma_{an})}{f^2}, \quad (1)$$

where φ– the angle taken from the condition of the cleaning device pass, deg.;

I – inertia moment of the pipe cross-section, m^4;

α – temperature coefficient of linear expansion of the pipe metal, 1/°C;

E – modulus of elasticity of the pipeline metal, Pa;

Δt –positive temperature difference, °C;

σ_{an} – annular stresses in the pipe wall from the calculated internal pressure, Pa;

f – compensator deflection, m.

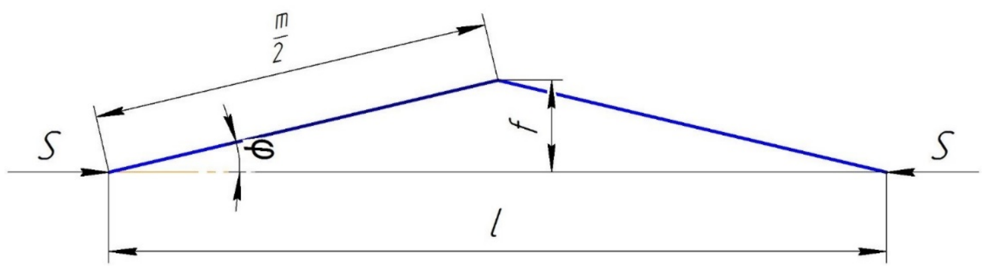

Figure 3 - Calculation scheme of the half-wave length «snake»: l –compensator length; f – compensator deflection; m – length of the compensator's arm

The described investigations in [31] and analysis of the expression (1) demonstrate that for the small deflection values f longitudinal force S reaches significant quantity. Thus, for small values of f compensating ability of the compensator (i.e., the ability to reduce the longitudinal force) is insignificant. The increase f leads to a monotone decrease S and the compensating ability growth.

In order to ensure the overall longitudinal stability of the underwater pipeline with the compensator application, the condition should be observed (2).

$$S \leq N_{cr}, \tag{2}$$

where N_{cr}– critical longitudinal compressive force, N.

Using the relation of $cos\varphi = \frac{l}{m}$, the condition (2) will have the form (3).

$$\left(\frac{l}{f}\right)^2 \cdot \frac{3 \cdot I}{m \cdot l} \leq \frac{N_{cr}}{\alpha \cdot E \cdot \Delta t + 0{,}2 \cdot \sigma_{an}}. \tag{3}$$

The condition (3) allows to take the geometric parameters of the compensator, based on the value of the critical force N_{cr}, temperature difference and operating pressure.

The analysis of the calculation procedure of the researched design according to [31] (Figure 3) demonstrates that the pipes connection at the top of the rotation angle, where the maximum deflection f, is made without the bends use. On the compensator boundaries, the pipelines are connected rectilinearly without the rotation angle. The proposed compensator construction at the top of the rotation angle and at the ends has a welded pipes connection with bends use. These design differences introduce some variation in the quantity of longitudinal force S. To determine the amount changes, the studies have been undertaken.

Therefore, the experiment purpose is the determination the amount changes in the longitudinal force of the compensating device according to the invention with bends use from a previously known compensating device structurally designed as a broken bolt.

When testing theoretical dependencies and the general revealing of the system's operation nature under load, there is not necessary to address the issue of the transition conditions from model to nature. In these cases, it is recommended to calculate the actual model and then compare the theoretical results with the appropriate experimental data.

When choosing the parameters of the physical model, it is necessary to take into account the condition (4):

$$\begin{gathered} \frac{3 \cdot E \cdot I \cdot \alpha \cdot \Delta t \cdot cos\varphi}{f^2} < N_0, \\ \frac{3 \cdot I \cdot cos\varphi}{f^2} < F, \end{gathered} \tag{4}$$

where N_0 – longitudinal force from the temperature difference for the straight pipeline sections, N; $N_0 = \alpha \cdot E \cdot \Delta t \cdot F.$

The basis on recommendations [31], conditions (4), and also taking into account the clearance conditions and diagnostics (radius bends is not less than $5 \cdot D_{out}$, where D_{out} – the outside pipeline diameter), the following parameters of the physical model of the compensating device have been taken: pipe diameter – 25 mm, wall thickness – 2 mm, and a length of 2.05 m will be consistent with deflections from 0.02 to 0.08 m. Maximum temperature difference $\Delta t = 50℃$ is chosen, based on actual and often encountered operating conditions.

The measured longitudinal force from the pipeline elongation caused by the change in the pipe walls temperature must be compared with the design force determined by formula (5):

$$S_d = \frac{3 \cdot E \cdot I \cdot \alpha \cdot \Delta t \cdot cos\varphi}{f^2}. \tag{5}$$

2.2. Description of the experimental setup

On a metal sheet – foundation 1 lenght 2.5 m and width 0.5 m support elements 2 are placed on which the compensator 3 is installed (Figure 4).

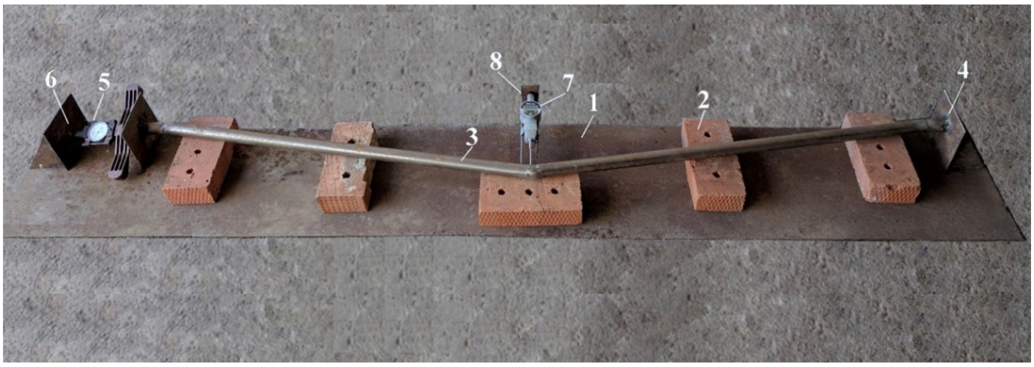

Figure 4. Elements of the experimental setup:

1 – metal foundation; 2 – support elements; 3 – compensator; 4 – displacement tether; 5 – compression dynamometer; 6 – dynamometer fastening system; 7 – displacement indicator; 8 – fastening system of displacement indicator

This is done that the pipe is prevented from making contact with the metal base during the study, since when the pipe is heated, the sheet may become deformed due to heating, which will give an error in the measurements.

Also, in order to rigidly fix the pipe during the experiment, it is necessary to provide displacement tether 4 which are also made of metal plates and welded to the base 1.

To fix the dynamometer 5 reliably during the experiment, we make a special fastening system 6, which consists of a nut and threaded stud. In the displacement tether, a hole is made, where a nut is then fastened.

The displacement indicator 7 is fixed by a clamp on a welded structure (the fastening system of displacement indicator 8) and is in contact with the compensator so that during the pipe heating the displacement measurement occurs.

The experimental setup scheme is shown in Figure 5.

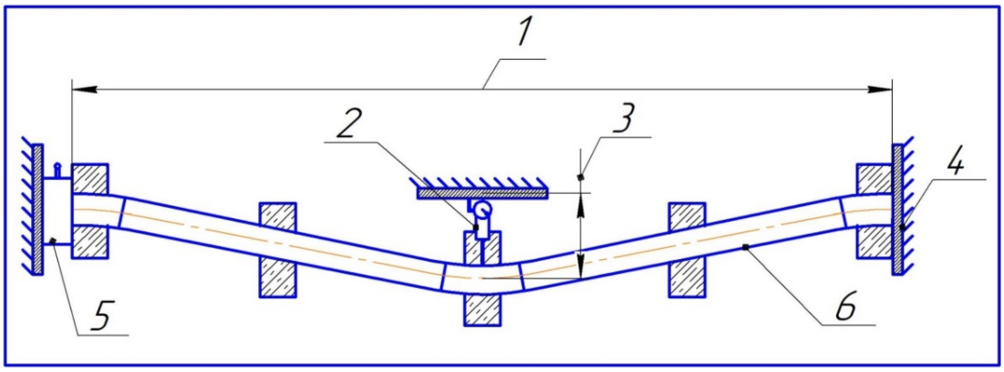

Figure 5. Diagram of the experimental setup:
1 – compensator length; 2 – displacement indicator; 3 – compensator deflection; 4 – stop; 5 – compression dynamometer; 6 – compensator

2.3. Experiment procedure

Experimental technique:

– measurement of temperature (contact thermometer) along the entire length of the pipe before the study;
– verification of the dynamometer reading (initial value must be set);
– uniform heating with gas burners use;
– measurement of force (dynamometer readings) and temperature measurement (contact thermometer readings), which occur during the temperature increases;
– control temperature measurement (indication of the contact thermometer) along the entire length of the pipe after the end of heating and fixing the indication of the dynamometer;
– analysis of the results.

Heating of the experimental the pipe pieces conducted simultaneously by several gas burners with the maximum possible uniform heating (+0 °C to +50 °C). The control measurements of temperature along the pipe length showed a temperature difference ± 3 °C.

During the experiment, as it was supposed, during heating of the pipe longitudinal force was recorded according to the indications of the dynamometer. This experiment was carried out for all physical models with the geometric characteristics given above.

During the study, we used the contact thermometer TK-5.01, the compression dynamometers DOSM-3-1U, DOSM-3-2U, DOSM-3-10U.

The error in the indicator readings of the IC-50 exceeded the permissible limits because of a violation of the device operating temperature, so further consideration of them is not advisable.

According to the theory of mathematical statistics, to reduce the random measurement errors to a confidence interval with a given reliability, the required measurements number was determined.

It was decided to conduct 8 measurements with confidence $\alpha = 0.9$.

3. Results and Discussion

Graphs of changes in the experimental and calculated values of the longitudinal force S from temperature difference Δt compensating device are demonstrated in Figures 6–9.

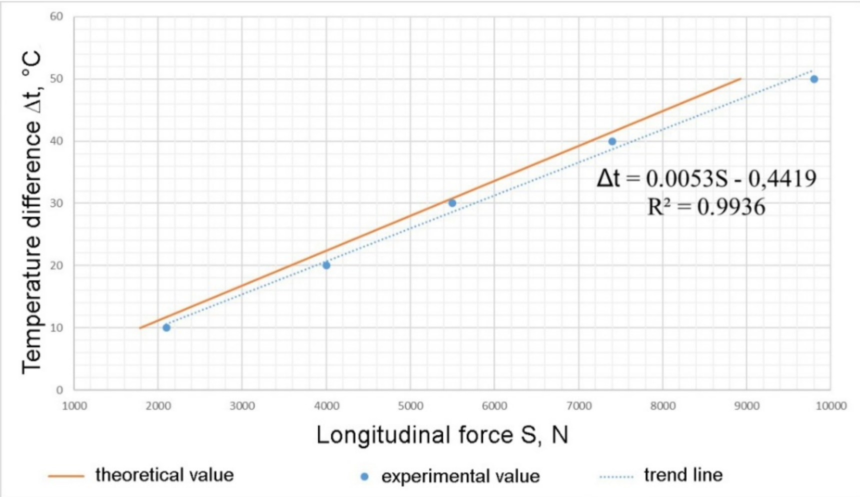

Figure 6. Graph of longitudinal force changing S from temperature difference Δt compensating device with deflection $f = 0.02$ m

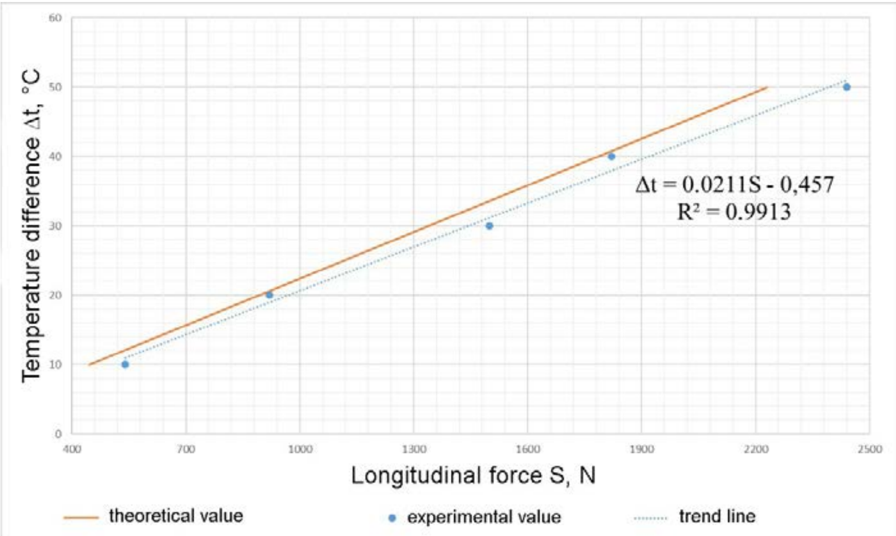

Figure 7. Graph of longitudinal force changing S from temperature difference Δt compensating device with deflection $f = 0.04$ m

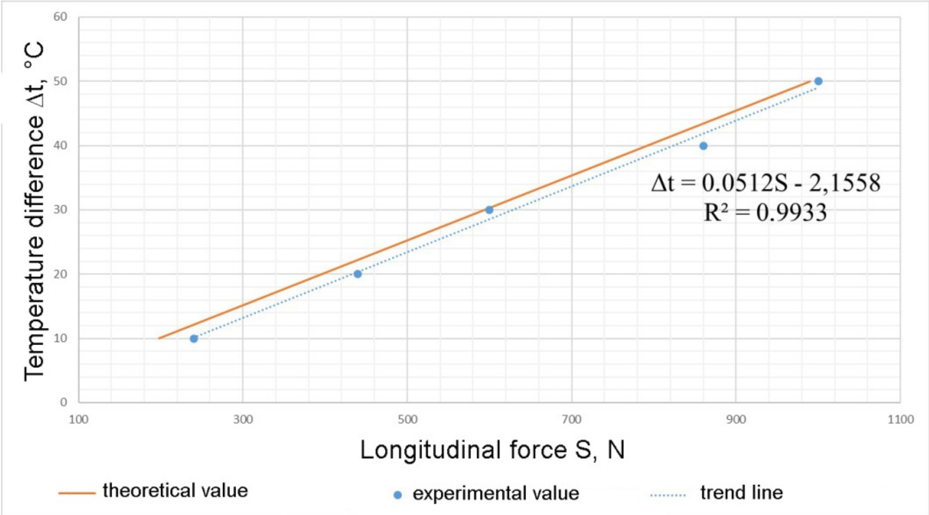

Figure 8. Graph of longitudinal force changing S from temperature difference Δt compensating device with deflection $f = 0.06$ m

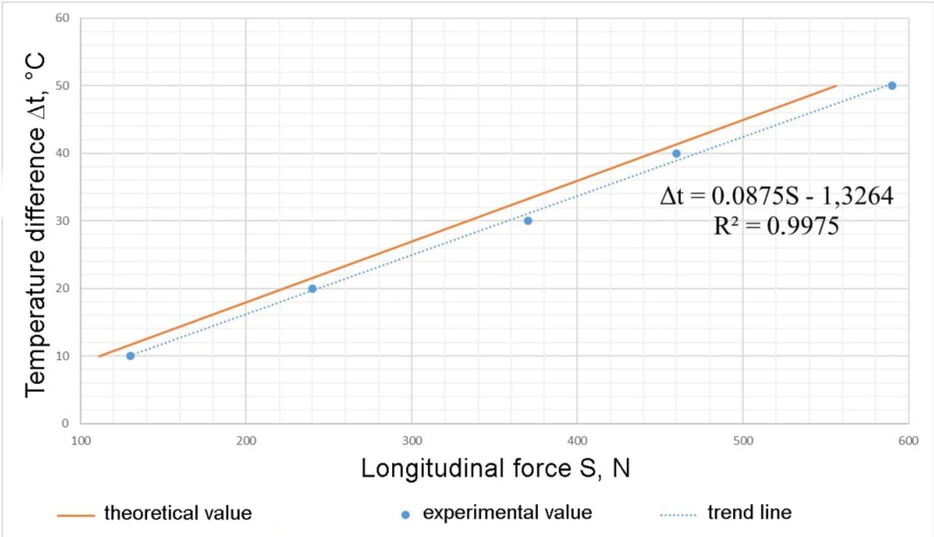

Figure 9. Graph of longitudinal force changing S from temperature difference Δt compensating device with deflection $f = 0.08$ m

As a result of the correlation analysis of the experimental data, the following is established:

– the correlation field showed a positive correlation between the value of the temperature difference and the longitudinal force obtained experimentally, that is, during an increase in one value, the other increases on average;

– for the analysis, an approximating curve was chosen in the form of a linear function;

– the selective correlation coefficient varies $r_{xy} = 0.93 \dots 0.96$, which indicates that a strong connection between the value of the temperature difference and the experimentally obtained longitudinal force.

As a result of the regression analysis, the following is established:

– using the least squares method the parameters of linear regression equations are obtained;

– estimate of the quality of the regression equations demonstrated an average relative error of approximation not exceeding $\overline{A} = 1.18\%$, which indicates a good selection of regression equations to the original data.

As a result of checking the adequacy of the mathematical model, the following is established:

– since the experimental Fisher test is larger than the tabulated values for all experimental curves, the determination coefficient is statistically significant, and the regression equation adequately describes the experimental data;

– verification of the coefficients significance of the regression equations in the Student's t-test shows that the statistical the coefficients significance is confirmed.

The graphs (Figures 6–9) show a systematic deviation of the measured value of the longitudinal force S_{ex} depend on the estimated S_d. Taking into account all the errors in the experimental measurements, it can be established that the design of the compensating device proposed by us changes the magnitude of the longitudinal force S_d by formula (5) for the broken bolt construction by a specific value, which varies from 0.851 to 0.902.

The value of the longitudinal force for the proposed design of the compensating device (6):

$$S_d = k \cdot S_{ex} \tag{6}$$

where k – refinement coefficient obtained as a result of experimental measurements.

This fact is explained that the proposed compensating device with the bends use has a more rigid design than the compensating device in the form of a broken bolt. Identifying the obtained value of the deviation for the refinement coefficient of the compensator form, it will take equal to $\mathrm{k} = 0.85$, taking into account in the calculations the most unfavorable loading case.

Consequently, the rational parameters of the proposed compensating device for underwater pipeline transitions in order to increase the overall stability in the longitudinal direction must be determined by the condition (7):

$$\left(\frac{l}{f}\right)^2 \cdot \frac{3 \cdot I}{m \cdot l} \leq \frac{k \cdot N_{cr}}{\alpha \cdot E \cdot \Delta t + 0{,}2 \cdot \sigma_{an}}. \tag{7}$$

As an example, an underwater gas pipeline of diameters $D = 530\ mm$, a wall thickness $\delta = 25\ mm$ for the case of the ground erosion over the pipeline on the entire length of the curved section equal to $l = 85\ m$. The lower critical force is equal to $N_{cr} = 8.4\ MN$, which does not provide the conditions for the overall pipeline stability in the longitudinal direction. Consequently, according to the formula (7), the rational parameters of the proposed compensating device are determined, for which the length is equal to $l = 50\ m$ and deflection $f = 2\ m$.

The authors of the work [31] considered the change in the longitudinal force from the compensating device parameters of a triangular shape, and also assumed that the cold bends change the parameter of the longitudinal force. But there were no specific recommendations, studies, analyzes in their work. They relied on the fact that the parameter of the change in longitudinal force would not be significant. However, as our studies have shown, the parameter of the longitudinal force varies by 15 %, which is quite significant in determining the stability of the pipeline.

An analysis was conducted of the stress-strain state of the proposed compensating device with the use of bent taps in comparison with the previously known compensating device, structurally made in the form of a broken bolt, by the finite element method in the software complex Ansys. The description of the numerical experiment is given in Table 1.

Table 1. Description of the numerical experiment

Name	Description
Geometry	Calculation is made using thick-walled cylindrical shells; the parameters of the models are assumed to be analogous to the laboratory experiment
Material	Steel grade K60 is specified with the following strength characteristics: tensile strength 590 MPa and yield strength 460 MPa.
Border conditions	The boundary conditions included the tasks of rigidly fixing the pipe ends with the help of the command Fixed Support
Loads and effects	In the section Loads thermal loads are specified with stepwise loading of 10 ° C to a maximum value of 50°C.

The results of calculations for compensators with a maximum deflection f = 0.08 m and a maximum temperature difference Δt = 50 ℃ are shown in Figures 10–11 in the form of stress fields and displacements from the graphic window of the software complex Ansys.

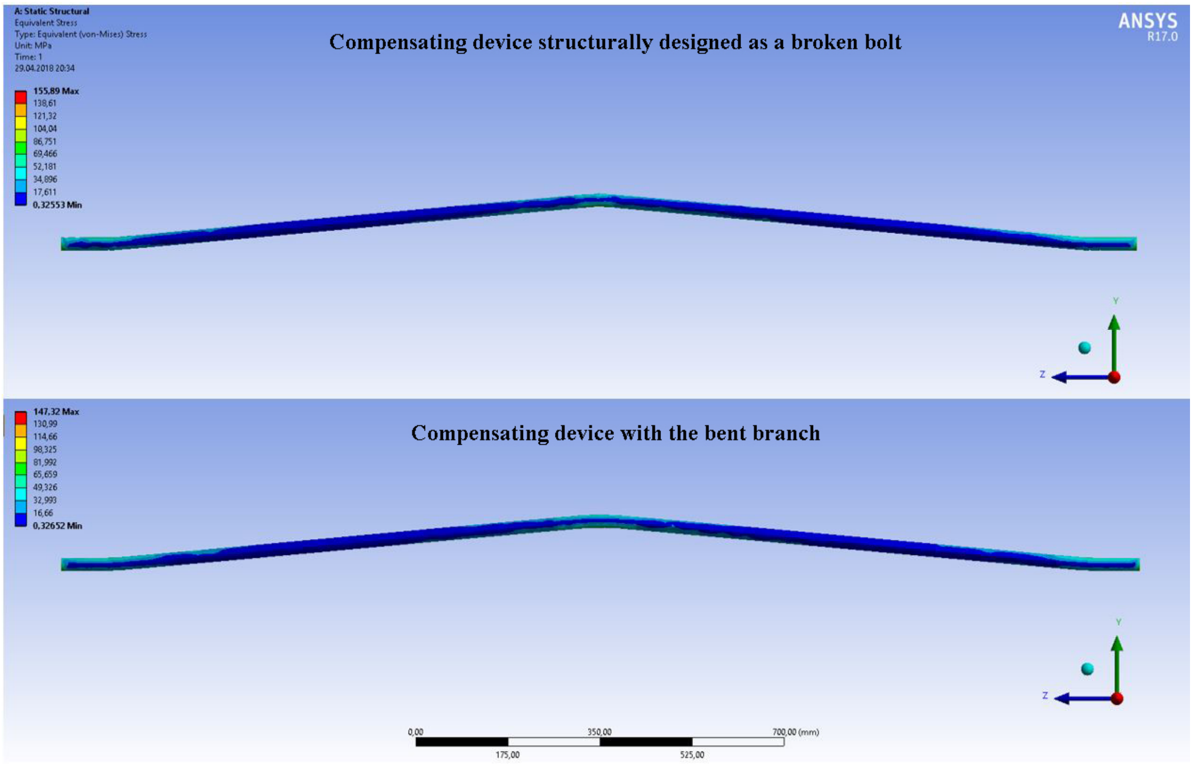

Figure 10. The stress field of the compensators

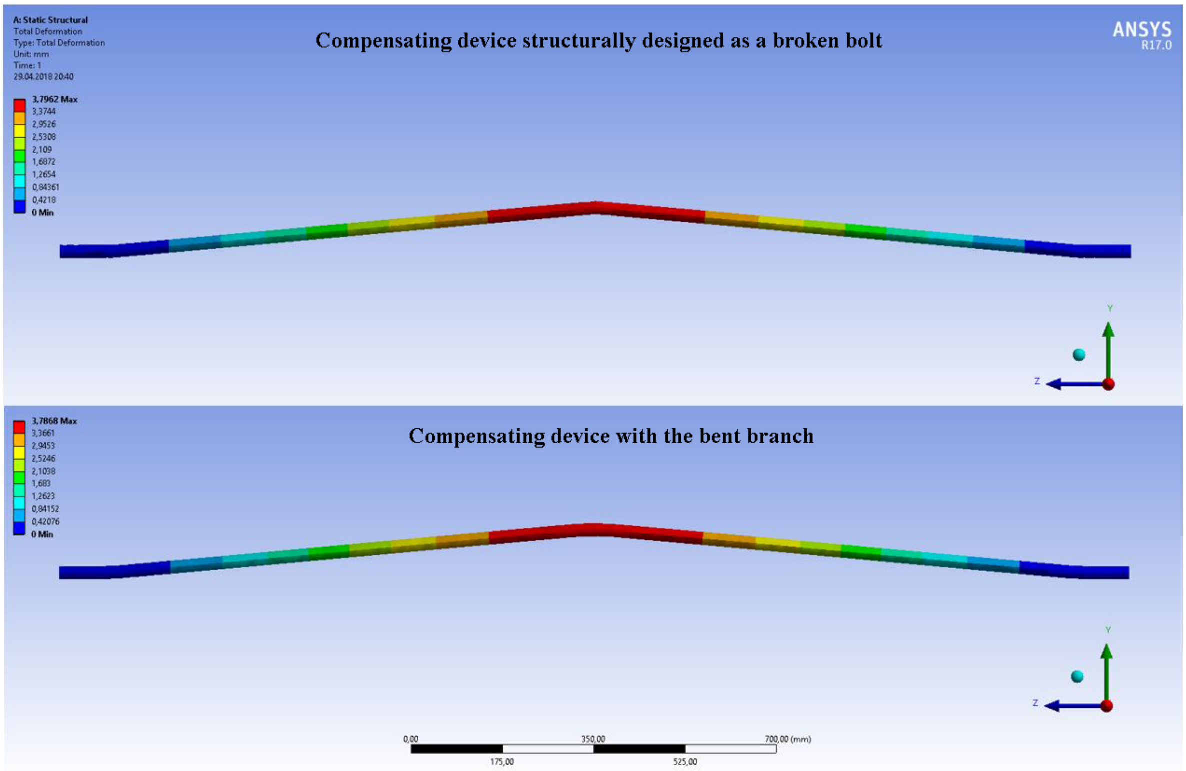

Figure 11. The field of displacement of the compensators

The values of movements do not practically change, however, the voltage in the proposed form of the compensator is less by 5.5%. In pipeline construction, this is the percentage reduction in the stress state in the pipeline is very significant. Consequently, the proposed form of the compensator, in addition to increasing the equivalent longitudinal force S by 15 %, also reduces the stress-strain state of the pipeline.

4. Conclusions

1. It has been determined that ballasting of adjoined areas allows to reduce the effect of the ultimate longitudinal force due to the temperature expansion of the pipeline material in the central part, and also during constructing underwater gas pipelines it is necessary to provide for the compensator facility at one of the ends of the underwater transition in the ground of adjoined areas to ensure the underwater transitions stability of gas and oil pipelines.

2. The refinement coefficient of the compensator shape, constructively obtained with the bends use, to reduce the longitudinal compressive force emerging from the temperature difference to the level of ensuring the overall pipeline stability in the longitudinal direction, which makes it possible to determine its rational parameters and is assumed to be equal $k = 0.85$.

3. For underwater pipeline transitions, taking into account the actual conditions of the laying according to the proposed technology, using elastically deformable materials or grounds for the free compensator displacement, the correction coefficient of the compensator form must not exceed $\mathrm{k} \leq 0.85$.

4. The proposed form of the compensator, in addition to increasing the equivalent longitudinal force S by 15%, also reduces the stress-strain state of the pipeline by 5.5%.

References

1. Kozhaeva K.V., Mustafin F.M., Yakupova D.Ye. Metody rascheta prodolnoy ustoychivosti truboprovoda i mery po yeye obespecheniyu na uchastke podvodnogo perekhoda [Methods of calculation of longitudinal stability of the pipeline and measure for her providing on the site of underwater transition]. *Neftyanoye khozyaystvo*. 2016. No. 2. Pp. 102–104. (rus)
2. Mustafin F.M., Abzalov A.K., Kozhaeva K.V. (Kutsenko K.V.), Mamliyev E.V. Diagnostika i raschet ustoychivosti truboprovoda na uchastke podvodnogo perekhoda [Diagnostics and calculation of stability of the pipeline on the site of underwater transition]. *Gazovaya promyshlennost*. 2013. No. 700. Pp. 41–43. (rus)
3. *Svidetelstvo o gosudarstvennoy registratsii programmy dlya EVM No. 2013615632.* Mustafin F.M., Kozhaeva K.V. (Kutsenko K.V.), Mamliyev E.V., Absalyamov E.R. Raschet ustoychivosti truboprovoda protiv vozdeystviya prodolnykh sil na uchastke podvodnogo perekhoda [Calculation of stability of the pipeline against influence of longitudinal forces on the site of underwater transition]. Zaregistrirovano v Reyestre programm dlya EVM 17.06.2013 g. Opublikovano 20.09.2013. (rus)
4. Filatov A.A. *Raschetno-eksperimentalnyye issledovaniya napryazhenno-deformirovannogo sostoyaniya podvodnykh perekhodov magistralnykh gazoprovodov*: dissertatsiya ... kandidata tekhnicheskikh nauk: 25.00.19 [Calculation-experimental studies of the stress-strain state of underwater transitions of main gas pipelines]. Institut problem transporta energoresursov. Moscow, 2013. 115 p. (rus)
5. Dudnikov Yu.V. *Nauchnyye osnovy proyektirovaniya i obespecheniya bezopasnosti slozhnykh uchastkov lineynoy chasti magistralnykh nefteprovodov*: dissertatsiya ... doktora tekhnicheskikh nauk: 25.00.19, 05.26.03 [Scientific fundamentals of designing and securing the complex parts of the linear part of the main oil pipelines]. Institut problem transporta energoresursov. Ufa, 2012. 366 p. (rus)
6. Filatov A.A. Mekhanicheskiye napryazheniya i peremeshcheniya truboprovoda na uchastkakh rechnykh podvodnykh perekhodov MG [Mechanical stresses and pipeline movements on sections of river underwater transitions of MG]. *Territoriya Neftegaz*. 2011. No. 9. Pp. 56–60. (rus)
7. Vagner V.V., Kushnir S.Ya., Pulnikov S.A. Raspredeleniye strely progiba arochnogo vybrosa po dline podzemnogo gazoprovoda [Arc arch deflection distribution along the

Литература

1. Кожаева К.В., Мустафин Ф.М., Якупова Д.Е. Методы расчета продольной устойчивости трубопровода и меры по ее обеспечению на участке подводного перехода // Нефтяное хозяйство. 2016. № 2. С. 102–104.
2. Мустафин Ф.М., Абзалов А.К., Кожаева К.В. (Куценко К.В.), Мамлиев Э.В. Диагностика и расчет устойчивости трубопровода на участке подводного перехода // Газовая промышленность. 2013. № 700. С. 41–43.
3. Свидетельство о государственной регистрации программы для ЭВМ №2013615632. Мустафин Ф.М., Кожаева К.В. (Куценко К.В.), Мамлиев Э.В., Абсалямов Э.Р. Расчет устойчивости трубопровода против воздействия продольных сил на участке подводного перехода // Зарегистрировано в Реестре программ для ЭВМ 17.06.2013 г. Опубликовано 20.09.2013.
4. Филатов А.А. Расчётно-экспериментальные исследования напряжённо-деформированного состояния подводных переходов магистральных газопроводов: диссертация ... кандидата технических наук: 25.00.19. Институт проблем транспорта энергоресурсов. Москва, 2013. 115 с.
5. Дудников Ю.В. Научные основы проектирования и обеспечения безопасности сложных участков линейной части магистральных нефтепроводов: диссертация ... доктора технических наук: 25.00.19, 05.26.03. Институт проблем транспорта энергоресурсов. Уфа, 2012. 366 с.
6. Филатов А.А. Механические напряжения и перемещения трубопровода на участках речных подводных переходов МГ // Территория Нефтегаз. 2011. № 9. С. 56–60.
7. Вагнер В.В., Кушнир С.Я., Пульников С.А. Распределение стрелы прогиба арочного выброса по длине подземного газопровода // Известия вузов «Нефть и газ». 2008. № 4. С. 101–104.
8. Rashidov T.R., An E.V. Geometrically nonlinear buckling stability analysis of axially loaded underground pipelines // Soil mechanics and foundation engineering. 2017. Vol. 54. № 2. Pp. 76–80.
9. Bai Y., Xu W.P., Ruan W.D., Tang J.W. On-bottom stability of subsea lightweight pipeline (LWP) on sand soil surface // Ships and offshore structures. 2017. Vol. 2. № 7. Pp. 954–962.
10. Carkovs J., Matvejevs A., Pavlenko O. Stochastic stability of a pipeline affected by pulsate fluid flow // ICTE

length of the underground gas pipeline]. *Izvestiya vuzov «Neft i gaz»*. 2008. No. 4. Pp. 101–104. (rus)

8. Rashidov T. R., An E. V. Geometrically nonlinear buckling stability analysis of axially loaded underground pipelines. *Soil mechanics and foundation engineering*. 2017. Vol. 54. No. 2. Pp. 76–80.
9. Bai Y., Xu W.P., Ruan W.D., Tang J.W. On-bottom stability of subsea lightweight pipeline (LWP) on sand soil surface. *Ships and offshore structures*. 2017. Vol. 12. No. 7. Pp. 954–962.
10. Carkovs J., Matvejevs A., Pavlenko O. Stochastic stability of a pipeline affected by pulsate fluid flow. *ICTE Conference.* Riga Tech. Univ., Riga, LATVIA, 2017. Vol. 104. Pp. 12–19.
11. Draper S., An H., Cheng L. Stability of subsea pipelines during large storms. *Philosophical transactions of the royal society a-mathematical physical and engineering sciences*. 2015. Vol. 373. No. 2033. Pp. 1–22.
12. Jha P. C., Balasubramaniam V. R., Sandeep N. Application of GPR in assessing the stability of oil pipeline. *15th International Conference on Ground Penetrating Radar (GPR).* Brussels, BELGIUM, 2014. Pp. 441–446.
13. Yu S. Y., Choi H. S., Lee S. K. An optimum design of on-bottom stability of offshore pipelines on soft clay. *International journal of naval architecture and ocean engineering.* 2013. Vol. 5. No. 4. Pp. 598–613.
14. Youssef B. S., Cassidy M. J., Tian Y. Application of statistical analysis techniques to pipeline on-bottom stability analysis. Journal of offshore mechanics and arctic engineering-transactions of the asme. 2013. Vol. 135. No. 3. Pp. 598–613.
15. Yang H., Wang A. Dynamic stability analysis of pipeline based on reliability using surrogate model. *Journal of marine engineering and technology*. 2013. Vol. 12. No. 2. Pp. 75–84.
16. Gaeta M. G., Lamberti A., Ricchieri F. Articulated concrete mattress for submarine pipeline protection: evaluation of the wave-induced forces and stability analysis. *6th International Conference on Coastal Structures*. Yokohama, JAPAN: 2013. Vol. 1-2. Pp. 1116–1125.
17. Azevedo-Perdicoulis T.P., Jank G., dos Santos P.L. Modelling a gas pipeline as a repetitive process: controllability, observability and stability. *Multidimensional systems and signal processing.* 2015. Vol. 26. No. 4. Pp. 967–984.
18. McMaster S.Y., O'Brien D., Scholtz D.E., Ryan J.R. On-bottom stability analysis for a pipeline on a mobile seabed. *31st ASME International Conference on Ocean, Offshore and Arctic Engineering.* Rio de Janeiro, Brazil: 2012. Vol. 3. Pp. 225–233.
19. Tian Y.H., Cassidy M.J., Chang C.K. Assessment of offshore pipelines using dynamic lateral stability analysis. *Applied ocean research.* 2015. Vol. 50. Pp. 47–57.
20. Meshkov Y.Y., Shyyan A.V., Zvirko O.I. Evaluation of the in-service degradation of steels of gas pipelines according to the criterion of mechanical stability. *Materials science*. 2015. Vol. 50. No. 6. Pp. 830–835.
21. Ji G.M., Li L.J., Ong M.C. A comparison of simplified engineering and fem methods for on-bottom stability analysis of subsea pipelines. *35th ASME International Conference on Ocean, Offshore and Arctic Engineering*. Busan, SOUTH KOREA: 2016. Vol. 1.
22. Kozhaeva K.V. *Obespecheniye stabilizatsii proyektnogo polozheniya podvodnykh perekhodov gazonefteprovodov*: dissertatsiya ... kandidata tekhnicheskikh nauk: 25.00.19 [Ensuring stabilization of design provision of underwater transitions of gas and oil pipelines]. FGBOU VO Ufimskiy gosudarstvennyy neftyanoy tekhnicheskiy universitet. Ufa, 2017. 139 p. (rus)
23. Muravyeva L., Vatin N. Elaboration of the method for safety assessment of subsea pipeline with longitudinal

Conference. Riga Tech. Univ., Riga, LATVIA, 2017. Vol. 104. Pp. 12–19.

11. Draper S., An H., Cheng L. Stability of subsea pipelines during large storms // Philosophical transactions of the royal society a-mathematical physical and engineering sciences. 2015. Vol. 373. № 2033. Pp. 1–22.
12. Jha P.C., Balasubramaniam V. R., Sandeep N. Application of GPR in assessing the stability of oil pipeline // 15th International Conference on Ground Penetrating Radar (GPR). Brussels, BELGIUM, 2014. Pp. 441–446.
13. Yu S.Y., Choi H.S., Lee S.K. An optimum design of on-bottom stability of offshore pipelines on soft clay // International journal of naval architecture and ocean engineering. 2013. Vol. 5. No. 4. Pp. 598–613.
14. Youssef B.S., Cassidy M. J., Tian Y. Application of statistical analysis techniques to pipeline on-bottom stability analysis // Journal of offshore mechanics and arctic engineering-transactions of the asme. 2013. Vol. 135. No. 3. Pp. 598–613.
15. Yang H., Wang A. Dynamic stability analysis of pipeline based on reliability using surrogate model. Journal of marine engineering and technology. 2013. Vol. 12. No. 2. Pp. 75–84.
16. Gaeta M.G., Lamberti A., Ricchieri F. Articulated concrete mattress for submarine pipeline protection: evaluation of the wave-induced forces and stability analysis // 6th International Conference on Coastal Structures. Yokohama, JAPAN: 2013. Vol. 1-2. Pp. 1116–1125.
17. Azevedo-Perdicoulis T.P., Jank G., dos Santos P.L. Modelling a gas pipeline as a repetitive process: controllability, observability and stability // Multidimensional systems and signal processing. 2015. Vol. 26. No. 4. Pp. 967–984.
18. McMaster S.Y., O'Brien D., Scholtz D.E., Ryan J.R. On-bottom stability analysis for a pipeline on a mobile seabed // 31st ASME International Conference on Ocean, Offshore and Arctic Engineering. Rio de Janeiro, Brazil: 2012. Vol. 3. Pp. 225–233.
19. Tian Y.H., Cassidy M.J., Chang C.K. Assessment of offshore pipelines using dynamic lateral stability analysis // Applied ocean research. 2015. Vol. 50. Pp. 47–57.
20. Meshkov Y.Y., Shyyan A.V., Zvirko O.I. Evaluation of the in-service degradation of steels of gas pipelines according to the criterion of mechanical stability // Materials science. 2015. Vol. 50. No. 6. Pp. 830–835.
21. Ji G.M., Li L.J., Ong M.C. A comparison of simplified engineering and fem methods for on-bottom stability analysis of subsea pipelines // 35th ASME International Conference on Ocean, Offshore and Arctic Engineering. Busan, SOUTH KOREA: 2016. Vol. 1.
22. Кожаева К.В. Обеспечение стабилизации проектного положения подводных переходов газонефтепроводов: диссертация ... кандидата технических наук: ФГБОУ ВО Уфимский государственный нефтяной технический университет. Уфа, 2017. 139 с.
23. Muravyeva L., Vatin N. Elaboration of the method for safety assessment of subsea pipeline with longitudinal buckling. Advances in Civil Engineering. 2016. Vol. 2016. 7581360
24. Сысоев Ю.С. Устойчивость подземного магистрального газопровода на обводненных участках трассы: диссертация ... кандидата технических наук: 25.00.19. Место защиты: Институт проблем транспорта энергоресурсов. Тюмень, 2012. 168 с.
25. Сысоев Ю.С., Кушнир С.Я., Пульников С.А. Пространственная устойчивость подземного магистрального газопровода на обводненных участках трассы // Известия вузов «Нефть и газ». 2012. № 1. С. 72–76.
26. Бахтизин Р.Н., Масалимов Р.Б., Зарипов Р.М., Шварева Е.Н. Моделирование напряженно-

buckling. *Advances in Civil Engineering*. 2016. Vol. 2016. 7581360.

24. Sysoyev Yu.S. *Ustoychivost podzemnogo magistralnogo gazoprovoda na obvodnennykh uchastkakh trassy*: dissertatsiya ... kandidata tekhnicheskikh nauk: 25.00.19 [Stability of the underground main gas pipeline on watered sections of the route]. Institut problem transporta energoresursov. Tyumen, 2012. 168 p. (rus)
25. Sysoyev Yu.S., Kushnir S.Ya., Pulnikov S.A. Prostranstvennaya ustoychivost podzemnogo magistralnogo gazoprovoda na obvodnennykh uchastkakh trassy [The spatial stability of underground main gas pipeline on the flooded sections of the route]. *Izvestiya vuzov «Neft i gaz»*. 2012. No. 1. Pp. 72-76. (rus)
26. Bakhtizin R.N., Masalimov R.B., Zaripov R.M., Shvareva Ye.N. Modelirovaniye napryazhenno-deformirovannogo sostoyaniya podzemnogo uchastka truboprovoda, sostavlennogo iz krivoy vognutoy ili vypukloy vstavki krivolineynym polym sterzhnem v uprugoy srede [Modeling of the stress-deformed state of the underground portion of pipe composed of convex or concave curve insert curved hollow shaft in an elastic medium]. *Neftegazovoye delo*. 2012. No. 6. [online]. URL: http://ogbus.ru/authors/Bakhtizin/Bakhtizin_5.pdf (date of reference: 10.09.2016). (rus)
27. Islamgaleyeva L.F., Zaripov R.M. Vliyaniye stepeni obvodneniya grunta prilegayushchikh podzemnykh uchastkov na napryazhenno-deformirovannoye sostoyaniye podvodnogo gazoprovoda [Influence of the degree of watering of the soil of adjacent underground sections on the stress-strain state of the underwater gas pipeline*]. Neftegazovoye delo*. 2011. No. 6. [online]. URL: http://ogbus.ru/authors/Islamgaleeva/Islamgaleeva _1.pdf (date of reference: 08.10.2016). (rus)
28. Islamgaleyeva L.F. *Napryazhenno-deformirovannoye sostoyaniye podvodnykh perekhodov magistralnykh gazoprovodov s uchetom izmeneniya stepeni vodonasyshchennosti grunta na prilegayushchikh podzemnykh uchastkakh*: dissertatsiya ... kandidata tekhnicheskikh nauk: 25.00.19 [Stress-strain state of underwater transitions of main gas pipelines taking into account changes in the degree of water saturation of the ground in adjacent underground areas]. Islamgaleyeva Liliya Faritovna; [Mesto zashchity: Ufimskiy gosudarstvennyy neftyanoy tekhnicheskiy universitet]. – Ufa, 2013. 179 p. (rus)
29. *Patent RF № 141422, 10.06.2014*. Mustafin F.M., Shammazov A.M., Kozhaeva K.V. (Kutsenko K.V.), Abzalov A.K., Absalyamov E.R., Mamliyev E.V., Mashin A.Yu. Dugoobraznyy kompensator dlya truboprovoda [An arc-shaped compensator for the pipeline]. Bulletin "Inventions. Utility Models". 2014, No. 16. (rus)
30. Mustafin F.M., Kozhaeva K.V. Eksperimentalnyye issledovaniya po umensheniyu prodolnykh usiliy ot temperaturnykh vozdeystviy na podvodnykh uchastkakh truboprovodov [Experimental studies on the reduction of longitudinal forces from temperature effects on underwater sections of pipelines]. *Truboprovodnyy transport: teoriya i praktika*. 2014. No. 5-6 (45-46). Pp .59–65. (rus)
31. Borodavkin P.P., Taran V.D. *Truboprovody v slozhnykh usloviyakh* [Pipelines in difficult conditions]. M.: Nedra, 1968. 304 p. (rus)

деформированного состояния подземного участка трубопровода, составленного из кривой вогнутой или выпуклой вставки криволинейным полым стержнем в упругой среде // Нефтегазовое дело. 2012. № 6. [Электронный ресурс]. URL: http://ogbus.ru/authors/Bakhtizin/Bakhtizin_5.pdf (дата обращения: 10.09.2016).

27. Исламгалеева Л.Ф., Зарипов Р.М. Влияние степени обводнения грунта прилегающих подземных участков на напряженно-деформированное состояние подводного газопровода // Нефтегазовое дело. 2011. №6. [Электронный ресурс]. URL: http://ogbus.ru/authors/Islamgaleeva/Islamgaleeva_1.pdf (дата обращения: 08.10.2016).
28. Исламгалеева Л.Ф. Напряженно-деформированное состояние подводных переходов магистральных газопроводов с учетом изменения степени водонасыщенности грунта на прилегающих подземных участках: диссертация ... кандидата технических наук: 25.00.19. Уфимский государственный нефтяной технический университет. Уфа, 2013. 179 с.
29. Патент РФ № 141422, 10.06.2014. Мустафин Ф.М., Шаммазов А.М., Кожаева К.В. (Куценко К.В.), Абзалов А.К., Абсалямов Э.Р., Мамлиев Э.В., Машин А.Ю. Дугообразный компенсатор для трубопровода // Официальный бюллетень Федеральной службы интеллектуальной собственности «Изобретение. Полезные модели». 2014, № 16.
30. Мустафин Ф.М., Кожаева К.В. Экспериментальные исследования по уменьшению продольных усилий от температурных воздействий на подводных участках трубопроводов // Трубопроводный транспорт: теория и практика. 2014. № 5-6 (45-46). С. 59–65.
31. Бородавкин П.П., Таран В.Д. Трубопроводы в сложных условиях. М.: Недра, 1968. 304 с.

Ksenia Kozhaeva,
+7(917)4702615; st_kafedra@bk.ru

Ксения Валерьевна Кожаева,
+7(917)4702615; эл. почта: st_kafedra@bk.ru

Кожаева К.В. Влияние параметров компенсирующего устройства на устойчивость подводного трубопровода // Инженерно-строительный журнал. 2018. № 4(80). С. 24–36.