UDC 624.9

Spatial Models Developed Using Laser Scanning at Gas Condensate Fields in the Northern Construction-Climatic Zone

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Wide exploration and industrial exploitation of hydrocarbon fields in Yamal Peninsula pose in front of construction and mining companies critical problems of efficient construction at constantly evolving fields taking into account climatic and geocryological conditions of their location. Yamal Peninsula is characterized by unstable soils, the mobility of which has a substantial impact on the changes in spatial arrangement of field facilities, not only in the direct process of construction, but also during their scale-up and equipment overhaul. The paper examines implementation of 3D spatial arrangement modelling of industrial facilities into the process of construction and installation works at hydrocarbon fields in the northern construction-climatic zone. The purpose of implementing this method combined with 3D spatial modelling of equipment connections lies in reliability and safety enhancement of the facilities throughout their entire lifespan. Authors analyze statement and solution of the problem associated with alignment and installation of prefabricated equipment and pipelines, taking into account advanced technologies of 3D design and modelling. The study examines a 3D spatial model with the elements of equipment connection geometry; the model is related to existing production facilities at the field. Authors perform an analysis and in mathematical terms formulate the problem of optimal spatial arrangement for such models. The paper focuses on typical deviations, occurring in the installation process of constructions and connection facilities, their spatial arrangement is modelled. Possible solutions are offered, as well as an algorithm of their implementation at an operating field.

Key words: field pipelines; 3D modelling; onshore laser scanning; Yamal; prefabricated construction

How to cite this article: Men'shikov S.N., Dzhaljabov A.A., Vasilev G.G., Leonovich I.A., Ermilov O.M. Spatial Models Developed Using Laser Scanning at Gas Condensate Fields in the Northern Construction-Climatic Zone. Journal of Mining Institute. 2019. Vol. 238, p. 430-437. DOI: 10.31897/PMI.2019.4.430

Introduction. Today Yamal-Nenetsk Autonomous Okrug is one of the most promising Russian regions regarding the extraction of natural gas and gas condensate. The beginning of industrial exploitation at the fields of Yamal Peninsula – primarily, Bovanenkovo, Kharasaveyskoye and Novoportovskoye, located above the Polar Circle – became a starting point of shaping a new resource center of hydrocarbon extraction both for domestic consumption and for export to all world regions by means of a pipeline system, belonging to the United Gas Supply System of Russia, and LNG terminals [11, 12]. For the period of 9 months in 2018 gas production in the region increased by 5.3 % compared to the same period in 2017 and reached 433.5 billion m^3, production of oil and gas condensate reached 39.4 million tons. There are around 70 companies-subsoil operators, the total number of fields exceeds 280 («Still Growing! In 9 Months of 2018 Yamal Increased Production of Natural Gas, Condensate and Oil» // Neftegaz.RU. URL: https://neftegaz.ru/news/view/176325-Vse-rastet-Na-Yamale-za-9-mesyatsev-2018-g.-uvelichilas-dobycha-prirodnogo-gaza-kondensata-i-nefti (access date 13.11.2018)).

Problem statement. According to current legislation («On the Assertion of Regulations Regarding Hydrocarbon Fields Development»: Decree of the Russian Ministry of Natural Resources from 14.06.2016 N 356. URL: https://rg.ru/ 2016/09/12/minprirodi-prikaz356-site-dok.html (access date 13.11.2018)), development of hydrocarbon reserves is a combination of technological stages, each of them involving certain construction and installation works at the production site (Fig.1). The whole lifespan of the field (excluding field preparation) is implemented according to an engineering development chart (EDC), or an engineering development project (EDP), determined by the subsoil operator.

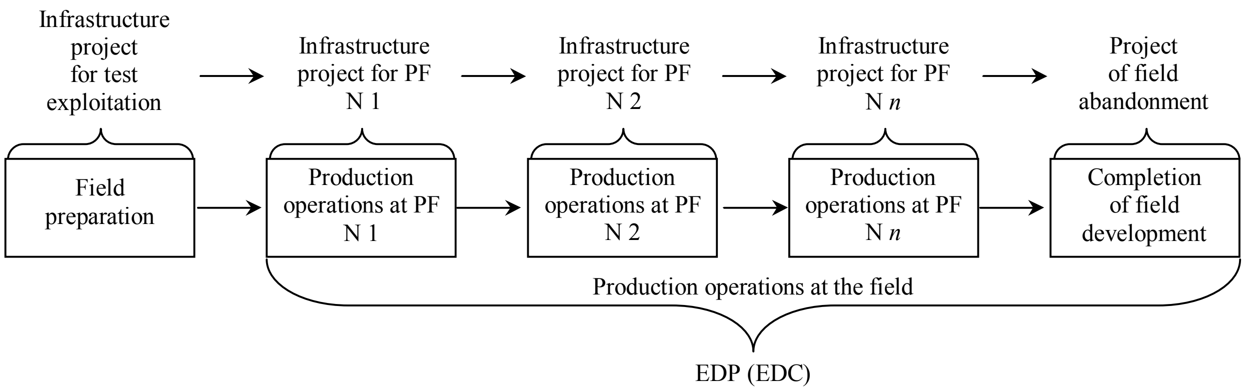

Fig.1. Organizational chart of field development

An engineering development project (or EDC) is determined for the field as a whole, in some cases specified in the «Regulations» – even for a group of fields, and contains project decisions, which will be implemented throughout the entire lifespan of the field; apart from that, certain production facilities (PF) are separated, which in a subsequent (or parallel-subsequent) order will be put into operation, as the production at the field moves forward.

Basing on EDP (EDC), PF infrastructure projects are developed along the lifespan of the field. These projects usually contain surface constructions for accumulation and in-field transportation of oil, gas condensate and reservoir water; engineering installations and equipment for pre-transportation hydrocarbon processing; maintenance equipment.

The processes of design and construction of the above mentioned equipment should include its engineering connection to the facilities already under operation in accordance with the general chart of field infrastructure in EDP (EDC). Moreover, at the stage of preparation for field's industrial exploitation, before EDP (EDC) is developed, it is required to design and construct a certain amount of wells, install wellhead equipment, separate elements of engineering machinery, etc. In subsequent exploitation and implementation of capital construction projects, these facilities should be taken into account and be technologically connected to the rest.

Hence, throughout the entire lifecycle of the field there is a need for coordination of engineering communications and equipment with each other and with already existing facilities, as well as to plan connecting elements for future projects of field development. As these operations are carried out both for underground elements of engineering machinery and pipelines and for surface facilities, they are greatly dependant on climatic and geocryological conditions of the region.

Compared to other oil and gas provinces in the north of West Siberia, Yamal is unique from the position of difficult climatic and geocryological conditions. The key factors are location of the region above the Polar Circle and presence of ice-rich saline permafrost rocks with exceptionally difficult geocryological conditions in the upper area of the section. Exceptional sensibility of permafrost rocks to anthropogenic impact leads to the instability of their location even under minimal man-made influence. The problem is magnified by the active geodynamic environment, high intensity of territorial denudation, overall development of exogenous geological processes and high background concentration of contaminants in the components of natural environment.

Under such conditions, implementation of each subsequent project of field development or commissioning of a new PF, requires, on the one hand, to reduce the amount of construction and installation works in the area, i.e., to reduce the intensity of anthropogenic influence on the unstable environment of the peninsula. On the other hand, due to technological complexity of producing equipment and pipelines, huge amount of works is needed to carry out their connection at the site.

Fig.2. Experimental installation for low-temperature separation with plate heat-exchangers

The first problem is actively solved by using prefabricated equipment and pipeline nodes [5], implementation of thermal soil stabilizations under the machinery and in-field pipelines and a general trend to transfer assembly and installation works to the territories of producing factories. At Bovanenkovo oil and gas condensate field, there was a delivery of prefabricated elements, including gas-pumping units, devices and installations for start gas, fuel gas and impulse gas treatment, boiler units, water treatment installations and many other fully functional technological modules, among which one must highlight an experimental installation for low-temperature separation (Fig.2).

The second problem concerning numerous abutting elements of field facilities and complex-geometry pipelines and their spatial arrangement up to this day is only solved using traditional methods of construction and production surveillance.

Construction and installation works, as well as exploitation of production facilities under permafrost conditions require constant geotechnical surveillance. Throughout the entire lifespan of the facilities there is a need to monitor multiple parameters, among them spatial arrangement of engineering machinery and PF constructions. Such activities are performed using geodetic equipment, step-by-step inspection of machinery and pipeline location during installation, which in case of deviations from the designed pattern leads to adjustment operations, and in separate cases, when abutting prefabricated nodes and encountering a significant deviation from the designed spatial arrangement of the elements – to the inability to continue installation without interference or screw joints. Described situation occurs due to insufficient information on the actual spatial arrangement of the objects directly before the beginning of installation works. In this case an effective solution to the problem would be to apply the technology of onshore laser scanning (OLS). It creates 3D real-geometry models, available for further processing in Cad-modelling software, which for different types of constructions in great detail has been described in studies [1, 3, 4, 6-8, 13]. OLS technology allows to quickly obtain 3D models of actual spatial arrangement and geometry of production facilities after their installation, to estimate deviations of abutting elements from their designed positions, to restore necessary geometry of the abutting nodes and using this geometry to adjust the node directly at the producing factory (or assembly platform) before sending it to the industrial site. The use of 3D models at oil and gas plants is widely spread for hydrocarbon deposits, e.g. [2, 9, 10].

Methodology. The most important factor in the implementation of OLS and 3D modelling is the estimation of necessary adjustments that the abutting member of engineering pipelines or equipment needs in order to minimize the amount of corrections «in place». To come to a solution and to estimate actual deviation in the sizes of abutting elements of engineering pipelines and machinery, as well as their geometric positioning, the mathematical description of the problem can be formulated as follows: *to identify such mutual spatial arrangement of engineering connection elements* (*pipes, fittings, shutoff and control valves*) *that satisfies all the regulations, requirements and constraints, and under the conditions of actual spatial arrangement of installed machinery and engineering pipelines is characterized by the minimal installation costs.*

For mathematical notation of this description it has been proposed to use the following optimization criterion: *discounted installation costs must be minimal*. In mathematical notation, criterion of optimization is presented with the formula:

$$S = S_c + S_i = S_1L_1 + S_2N_2 + S_3N_3 + f(M_f, Y_f),$$

where S_c – cost of connection elements; S_i – cost of installation works.

The cost of connection elements includes: the cost of 1 m of pipeline S_1, pipeline length in the i^{th} variant of connection L_1; the cost of fitting S_2, amount of fittings in the i^{th} variant of connection N_2; the cost of shutoff and control valves S_3, amount of shutoff and control valves in the i^{th} variant of connection N_3. The cost of installation works is an estimation of installation cost and is characterized by an empirical dependency on time required to perform installation works t_i, which in its own turn depends on actual installation deviations M_a and actual level of assemblability Y_a:

$$S_i = f(t_i) = f(M_a, Y_a).$$

Design level of assemblability Y_d is set up in accordance with the company's standard STO 02494680-0033.1-2004, numerical value of Y_d is defined by assemblability coefficient K_a, defined as a ratio of actual tolerance Δ_a to the technological one Δ_t:

$$K_a = \Delta_a / \Delta_t.$$

Design of a metal structure (including an engineering connection) contains the projected value of assemblability coefficient K_a, where Δ_a is determined from the condition of equipment's functionality according to the state standard GOST 26607-85, Δ_t – according to the precision of location survey by GOST 21779-82. In accordance with the company's standard STO 02494680-0033.1-2004, minimal acceptable values of K_a are specified. The actual value is estimated using a 3D real geometry model after OLS.

Actual deviation of the installation M_a is determined using a 3D model of spatial arrangement and is an estimate of actual deviation by the company's standard STO 02494680-0033.1-2004. Actual installation deviation M_a is a quantitative expression of systematic and random errors, accumulated in the process of operations and measurements.

Systematic errors occur under the influence of a permanently active factor, do not vary (or vary according to a certain law) in the course of a technological process and have a constant sign. An example of those is an error due to equipment failures. In such case, it should be eliminated.

Random errors do not have any consistent patterns, neither in the value, nor in the sign. In order to estimate them, actual data from the modelling of real spatial arrangement by means of OLS is used.

For a design construction, actual deviation of the installation M_a and actual level of assemblability Y_a are estimated as results of modelling of actual spatial arrangement of basic and abutting planes.

A mathematical model is determined as follows: *to find such an option of connection tracing* T_d (x_0, y_0, z_0) *from the variety of acceptable tracing options, for which the condition of the given optimal criterion – minimal discounted cost – would be satisfied.*

In the mathematical notion the model is presented with the formula

$$T = \arg\min \{S(T) \mid T \in T_p\}.$$

To solve this model, the following constraints have been determined: domain of the solution search, elements fixed in space; mathematical model of the connection arrangement, tracing model, deviations model, etc.

DOI: 10.31897/PMI.2019.4.430

Domain of the solution search. Authors focus on a rectangular system of coordinates *XYZO* with a space metric ρ, the selection of which is conditioned by the requirement to perform utility engineering along the coordinate axes:

$$\rho(c',c'')=\left|X_{c'}-X_{c''}\right|+\left|Y_{c'}-Y_{c''}\right|+\left|Z_{c'}-Z_{c''}\right|,$$

where $\rho(c',c'')$ – distance between points c' and c'' in *XYZO* space.

The space is bounded in such a way that:

$$X_c^{\min}\le X_c\le X_c^{\max};\quad Y_c^{\min}\le Y_c\le Y_c^{\max};\quad Z_c^{\min}\le Z_c\le Z_c^{\max}.$$

Elements fixed in space. Let there be two planes (hereafter – basic planes), between which the connection element needs to be placed (Fig.3). The planes are fixed in space and correspond to the actual location of abutting members of the machinery on the one hand, and field pipeline on the other. Each of the basic planes is defined in the *XYZO* space by the plane equation:

$$A_1x+B_1y+C_1z+D_1=0; \tag{1}$$

$$A_2x+B_2y+C_2z+D_2=0. \tag{2}$$

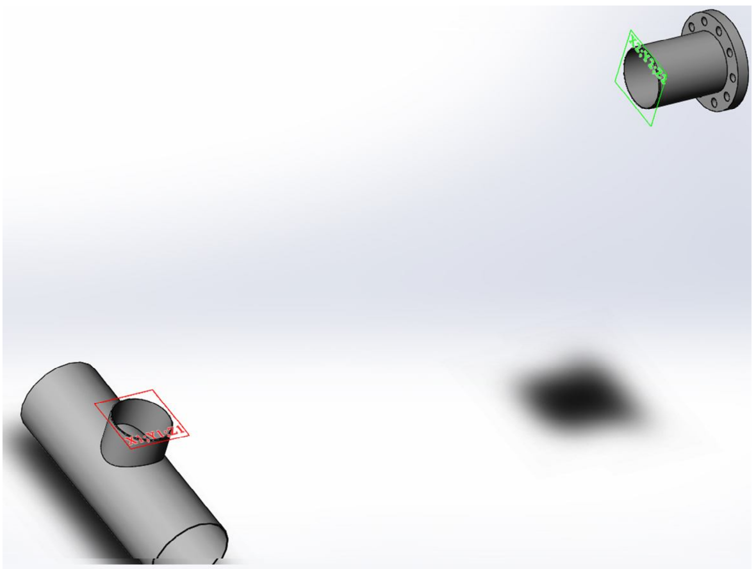

Fig.3. Tracing space with basic planes, specified by equations (1) and (2)

Abutting elements (mathematical simplification of the pipeline welded joint) are essentially circles of equal diameter (2*R*), located in the given planes. The centers of circles in the basic planes are specified by the points $M_1(X_1, Y_1, Z_1)$ and $M_2(X_2, Y_2, Z_2)$.

Mathematical model of the connection arrangement. Spatial arrangement of the connection is presented by a combination of elements L_1, N_2, N_3 and two planes (hereafter – abutting planes), which describe the abutting joint between the engineering equipment on the one hand and a pipeline on the other (Fig.4). Abutting planes are specified as the planes in the *XYZO* space:

$$A_1'x+B_1'y+C_1'z+C_1'=0;$$

$$A_2'x+B_2'y+C_2'z+C_2'=0.$$

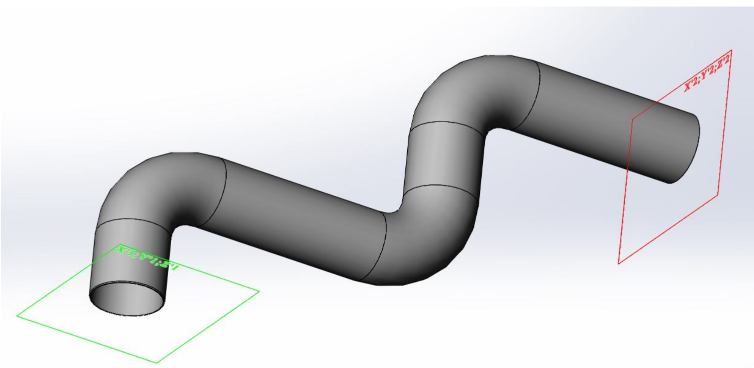

Fig.4. Connection model with abutting planes

Abutting elements (mathematical simplification of the pipeline welded joint) are essentially circles of equal diameter (2*R*). The centers of circles in the basic planes are specified by the points $M_1'(X_1', Y_1', Z_1')$ and $M_2'(X_2', Y_2', Z_2')$.

DOI: 10.31897/PMI.2019.4.430

Tracing model. Under tracing we will understand a certain combination of connection elements L_1, N_2, N_3, arrangement of basic and abutting planes, which shape certain values of Y_d and M_d (Fig.5).

Under design tracing we will understand a certain combination of connection elements L_1^d, N_2^d, N_3^d, designed arrangement of basic and abutting planes, which correspond to design values of Y_d and M_d. Design tracing is specified in design charts, projected values of Y_d and M_d – in installation sizes of design charts.

Under actual arrangement of the basic planes we will understand their location after installation works. Actual location is different from the designed one, which makes it impossible to install designed connections and maintain designed values of Y_a and M_a.

Deviations model. Deviation assessment during jointing is performed using two parameters: disalignment of circle centers D and deviation of planes (basic and abutting) from the parallel line φ. «Modelled» joint is coaxial, with abutting planes being parallel and the gap between them satisfying the requirements of the applied welding technology (Fig.5).

Each tracing option is characterized by certain values of disalignment between the centers of abutting circles D:

$$D_1 = \sqrt{(X_1 - X_1')^2 + (Y_1 - Y_1')^2 + (Z_1 - Z_1')^2}\ ;$$

$$D_2 = \sqrt{(X_2 - X_2')^2 + (Y_2 - Y_2')^2 + (Z_2 - Z_2')^2}$$

and certain parallel deviations of abutting planes from corresponding basic ones:

$$\cos\varphi_1 = \frac{A_1A_1' + B_1B_1' + C_1C_1'}{\sqrt{(A_1^2 + B_1^2 + C_1^2)(A_1'^2 + B_1'^2 + C_1'^2)}}\ ;$$

$$\cos\varphi_2 = \frac{A_2A_2' + B_2B_2' + C_2C_2'}{\sqrt{(A_2^2 + B_2^2 + C_2^2)(A_2'^2 + B_2'^2 + C_2'^2)}}\ .$$

Then M_a is a function of D and cosφ:

$$M_f = f(D_1; D_2; \cos\varphi_1; \cos\varphi_2)\ .$$

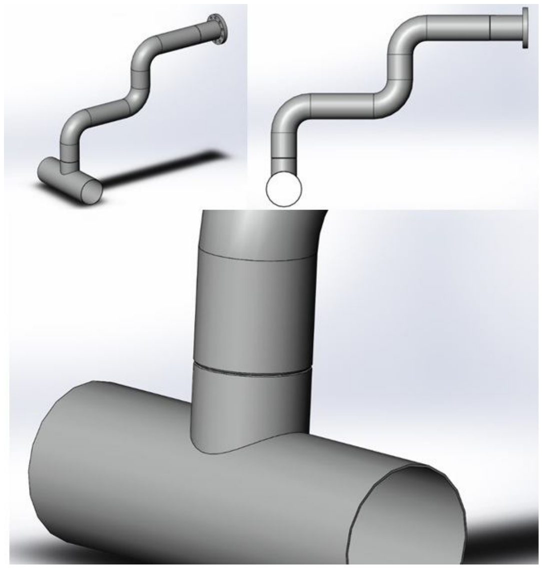

Fig.5. Model tracing with an «ideal» butt joint between the basic and the abutting planes (abutting elements are parallel, $\cos\varphi_1 = 1$, coaxial, even gap of $D = 5$ mm ensures the quality of welded joint)

For the planes there are acceptable levels of model deviations. Under model deviations we will understand the following:

• deviation of the gap between abutting planes, the planes still being coaxial and parallel (Fig.6);

• deviation of coaxial alignment, the planes still being parallel (Fig.7);

• deviation of coaxial and parallel alignment between abutting planes (Fig.7).

In real life, all the described model deviations take place, forming actual deviation values, expressed through D and cosφ.

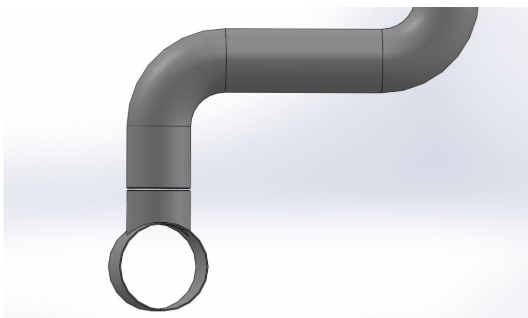

Fig.6. Model deviation along Z axis (abutting elements are coaxial and parallel, $\cos\varphi = 1$, but the bridging gap of $D = 25$ mm renders the welding impossible)

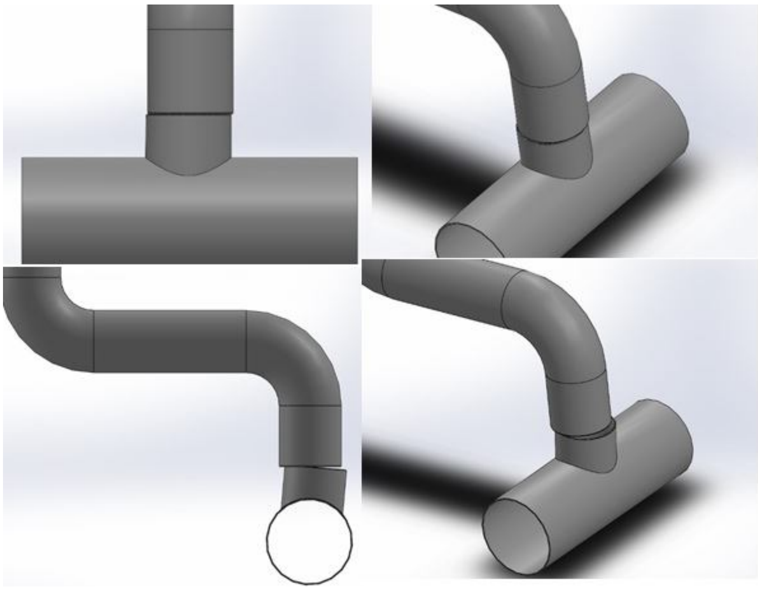

Fig.7. Model deviation in *XY* plane
(axes of abutting elements deviate by 25 mm in the joint plane, assembly without interference is impossible) and model deviation from parallel alignment of abutting planes (deviation angle equals 5°, $\cos\varphi_1 = 0.996$, assembly without interference is impossible)

Fittings, shutoff and control valves have constant geometry and rotation angle, which are determined depending on the pipeline diameter and standard requirements for corresponding products.

Minimal length of straight pipeline segments and minimal number of shutoff valves have been specified.

Design parameters for the level of assemblability Y_d and boundary levels of installation deviations M_d have also been assigned values, which represent initial conditions for the modelling of initial piping arrangement. Under the influence of random errors in the process of construction and installation works, their actual values may change, their estimation is performed by means of 3D modelling of the actual spatial arrangement.

Discussion. The implementation of current mathematical model is a sequence of the following processes:

1) construction of a 3D space (x_0, y_0, z_0) taking into account actual spatial arrangement of basic and abutting planes;

2) definition of the designed spatial arrangement of basic and abutting planes;

3) estimation of Y_d and M_d variations, taking into account actual spatial arrangement of basic and abutting planes; calculation of actual Y_a and M_a values;

4) search for an optimal tracing T upon S criterion with a regard to actual spatial arrangement of basic and abutting planes, calculation of optimal Y and M values;

5) adjusting the connection node for optimal tracing;

6) installation of the connection node with a regard to the mentioned changes.

Conclusion. Normative documentation does not contain precise wording for the accuracy of estimating vertical and horizontal deformations of buildings and constructions, or their periodicity for permafrost conditions. Moreover, in the northern construction-climatic zone natural and climatic factors have significant impact on the accuracy of geodetic works and stability of deep benchmarks, which are supposed to maintain stability of their height throughout the entire productive time of the object under surveillance and to ensure that in case of construction yielding it can be registered timely and with the necessary degree of precision. The application of laser scanning will allow to enhance the precision of assembly component connection of field machinery and engineering structures under the deformation of their spatial arrangement in difficult climatic and geocryoclogical conditions in the Yamal Peninsula.

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The paper was received on 14 February, *2019.*

The paper was accepted for publication on 5 April, *2019.*