General methodological foundations of measurement accuracy control

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Abstract. The article discusses the issues related to quality control of the construction of engineering structures, the approach to the accuracy of performing geodetic measurements at the current pace of construction and installation work, as well as during operation.

Introduction
The role of geodetic works in the construction of engineering structures and installation of technological equipment has recently significantly increased. Particular attention is paid to quality control of construction and installation works, increasing the requirements for the structural geometric parameters’ accuracy, its structural elements. At the same time, a sequence of technical measurements is required at all stages of both manufacturing and installation of equipment. Deviation from the design dimensions should not exceed the established tolerances. The accuracy of geodetic measurements is regulated by SNiPs and other regulatory documents for the work production.

However, the compliance with the requirements established by the regulatory documents on the required accuracy of performing geodetic measurements at the current pace of construction and installation work is not justified. Sometimes it is necessary to use such a measurement technique that allows to ensure the required accuracy, which complicates the process of construction and installation work, i.e. they either slow down or pause the survey duration. Therefore, when using geodetic methods for monitoring the technical condition of a structure or equipment both during construction or installation, and during operation, a different approach to the measurements’ accuracy is possible: necessary and sufficient. Moreover, two different approaches can be used to the object itself:

1) when its geometry is formed;
2) when the technical condition of the structure is determined.

We will proceed from the assumption that, starting work, we know nothing about the object from the point of view of its state.

In accordance with the stages of the engineering objects’ existence, their geometry can be represented as:

1) nominal;
2) design;
3) actual;
4) deformative.

Thus, the technical condition of any object at various stages can be represented by the following graph (Figure 1).
Figure 1. Technical condition stages of an object.

At the initial stage, during the period of construction and installation work, the geometry of the object is formed [1]. Its geometry changes from zero to 100% of the operational reliability. It should be borne in mind that the general state of the object consists of its actual state, taking into account the deviations arising from the technology of manufacturing individual structures and the production of construction and installation works, as well as deformation changes occurring due to an increase in the base loads, deformations of the Earth’s surface on the site and other factors (Figure 2).

The next stage can be described as the operational period. At this stage, during the operation of an engineering structure, its geometry changes as a result of deformations arising from its elements’ aging, equipment wear and a number of other reasons [2]. Consequently, its operational reliability is reduced. In this case, it becomes necessary to improve its reliability, i.e. a recovery period arises, as a result of which the object again reaches 100% operational reliability [3]. The last two periods can alternate repeatedly during the entire operation time of the structure. Ultimately, the object can undergo significant deformation changes, and, therefore, its geometry changes. In this case, elastic deformations transform into plastic ones, which leads to the destruction of the object.

According to Figure 2 an increase in deformation characteristics is observed at the initial stage. After the object has reached operational reliability, its deformation characteristics somewhat stabilize, although over time they continue increasing. Therefore, the technical condition of the object due to the resulting deformations will be a function of time $t$, i.e.

$$\xi_d = f(t).$$

While the actual geometry is formed up to 100% of operational reliability, after its formation it remains constant, i.e.

$$\xi_f = \text{const.}$$

The overall geometry is composed of the actual geometry and the geometry formed under the influence of the arising deformations, i.e.

$$\xi_0 = \xi_f + \xi_d.$$
By establishing tolerances, and, consequently, determining the accuracy of geodetic measurements, it becomes necessary to assess the readiness of a structure for operation. Let us take the following approach to the assessment. Depending on the ratio of the structure parameters to the technological tolerances $\delta$, let us consider the readiness of the structure, i.e. if the object is not ready for the operation, then the degree of its readiness $\xi$ can be taken as zero, and in the case when the structure is completely ready, $\xi = 1$. Moreover, all its parameters correspond to the established tolerances. In all other cases, it is possible to talk about a partial readiness degree, estimated in fractions of a unit in the interval from 0 to 1. Therefore, depending on the readiness degree of the object, it is possible to establish sufficient and necessary accuracy of geodetic work (Figure 3).

**Figure 2.** Forming the geometry of objects.

**Figure 3.** Graph of measurement accuracy $m$ dependence on the operational reliability degree: I - when forming the geometry; II - when determining the technical condition of an object during operation.

Considering that at each stage of the state of the structure, a different approach to the accuracy of the production of geodetic works is carried out, we will establish the following mean square errors for measurements.
Let us consider the attitude to the accuracy of geodetic control at the initial stage, when the geometry of any technological equipment is still being formed [4]. At this stage of geodetic measurements, it is possible to use sufficient accuracy, i.e. below the norm. The root mean square error of the measurement result in this case will be a function of the maximum deviation of the parameters of the structure from the design:

\[ m = C \cdot \Delta_{des}, \]  

(4)

where \( m \) – is a mean square error of the measurement result;
\( C \) – is a precision factor;
\( \Delta_{des} \) – is the maximum deviation of the parameters of the structure from the nominal.

As it can be seen from the graph (Fig. 3) when forming the object’s geometry, the closer the technical state of the structure to the readiness level, the more reliable the information about the geometric parameters of our object should be, the less uncertainty, therefore, the measurement accuracy should increase.

After the facility commissioning, the accuracy requirements are sharply reduced, since in this case the necessary and sufficient information that the technical condition meets the operational standards, all the parameters of the structure do not go beyond the maximum permissible values, is required. Over time, the object is subjected to deformation measurements for a number of reasons, since the deformations occurring during this period are superimposed on its general geometry (Fig. 2). When the state of an object approaches a critical stress-strain ratio, the level of uncertainty should be significantly reduced, therefore, the requirements for the accuracy of geodetic measurements increase.

This approach will significantly reduce the time spent on construction and installation work. An example of this is the performance of geodetic control of the controlled object radial overhead travelling crane installation.

At the initial stage of the geodetic works’ production, the accuracy coefficient was taken equal to 0.1. With the maximum deviation of the track axis points from the design 30 mm, the mean square error was 3.0 mm. As a result of the reassembly work, the largest deviations (15-30 mm) were first eliminated.

With further refinement of the track position, the accuracy of the work increased. At the second stage, the calculation of the root mean square error was made from the technological tolerance \( \delta_{max} \), i.e.

\[ m = C \cdot \delta_{max}. \]  

(5)

The accuracy coefficient at this stage of work was taken from 0.3 to 0.1 of the tolerance, therefore, the root-mean-square error was 0.7 mm.

This made it possible to obtain the actual state of the rail track axis, which differs from the design one within the established tolerances. At the same time, the time for stopping installation work for the production of geodetic observations has significantly decreased.

Thus, the object after installation has reached a state where its readiness degree \( \xi = 1 \). The object is ready for operation. In the future, during operation, the structure or equipment is periodically subjected to geodetic control, taking into account the regulatory documents’ requirements. According to the graph (Fig. 3), in this case, the technical condition of the object should be within the permissible values and the production of geodetic measurements can be performed with a lower accuracy in order to assess the technical condition of the object. In this case, to calculate a sufficient root mean square error of measurement, it is possible to use the dependence (5), taking the accuracy coefficient equal to 0.5. The root mean square error of measurement with a tolerance of 2.0 mm is 0.1 mm. To judge the object state, and in this case, the position of the overhead travelling crane path axis, such accuracy is quite enough.

Further operation of the structure leads to the fact that its elements, structures, individual parts are subject to wear, there is a displacement of the axes relative to the original position. The parameters deviate from the designed ones; therefore, the structure changes its technical condition. The degree of its readiness from 1 takes on the value \( < 1 \). If earlier it was stated that it was possible to use a sufficient degree of accuracy, now the more the structure deviates from its design position, the higher the accuracy of geodetic control over its condition. This is due to the fact that there is a limit of both the stress-strain
state and the deviations of its structures from the designed ones for any structure. Further, even a slight movement of structural or equipment elements can lead to its destruction. Therefore, in such a period, the most reliable, most detailed information about the slightest changes occurring with the state of the structure is needed. To establish the accuracy of geodetic works, it is also possible to use the dependence (5), while setting the accuracy coefficient as $C = 0.1$.

A similar approach was taken when determining the technical condition of residential buildings. At the preliminary stage, when it was required to determine their technical condition, the definition of the rolls was carried out by the theodolite by projecting the upper corners of the buildings onto a horizontal ruler. The accuracy of determining the rolls was from 5 to 10 mm. This accuracy is quite enough to assess the state of the structure when the rolls reached 10, 20 or more centimeters.

When leveling the buildings, when it was required to set the values of the single point displacements on the plane, the accuracy of geodetic control over the rise of houses should be much higher. In this case, an electronic total station was used [5], the accuracy of work on determining the points coordinates on the building was about 1 mm. Especially such accuracy provided a high-quality rise of houses at the final stage.

Summary
As it can be seen, using the example of two objects, the proposed approach to the accuracy of geodetic control of the structure geometry during its formation and determination of its technical state is fully justified. Moreover, on the one hand, it facilitates the surveyors’ work, on the other hand, it reduces the construction and installation work downtime during the period of geodetic measurements.

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