Features of monitoring bearing structures in the scientific and technical support of construction

Sergey Muzychenko*, and Dmitry Topchiy
Moscow State University of Civil Engineering, 129377, Moscow, Russia

Abstract. The purpose of this article is to analyze the possibility and feasibility of using forms and methods of scientific and technical support to increase the efficiency of monitoring the properties and states of load-bearing structures.

The task is to substantiate and develop an algorithm for assessing and predicting the states of load-bearing structures while monitoring the parameters of the effects on external and internal environment of construction production.

Research methods are systematic approach to the analysis of the conditions for obtaining relevant and reliable information data on the states of bearing structures being erected.

Research hypothesis - expanding the scope of scientific and technical support in the format of predicting possible changes in properties and states will significantly increase the efficiency in monitoring carried out during the construction of load-bearing structures and suitable for assessing the subsequent operational suitability of construction facilities.

The result of this research is a mathematical model for predicting changes in properties and states during the construction of load-bearing structures.

In recent years, due to increasing volume of construction of high-rise buildings, the relevance of such a line of activity as scientific and technical support of construction is growing. In comparison with technical supervision, which has the task of monitoring the activities of contractors, scientific and technical support of construction (STSC) has both an applied and a scientific approach, specifically, it develops and implements new construction methods, as well as modern materials, in order to obtain maximum efficiency and saving money and labor costs during construction and installation work.

The very definition of scientific and technical support sounds like this - a set of works of scientific and analytical, methodological, informational, expert control and organizational nature carried out by specialized organizations in the process of survey, design and erection of construction facilities in order to ensure the quality of construction, reliability (safety, functional suitability and durability) of buildings and structures, taking into account the applied non-standard design and technical solutions, materials and structures.

*Corresponding author: muzichenko.mgsn@mail.ru
1 Introduction

In many ways, STS is an additional link in the development of project documentation, as well as in the direct construction of a unique building or structure.

The need to apply STS is caused by the fact that the process of developing a project for the construction of unique high-rise buildings with a height of more than one hundred meters is not reflected in the regulatory documents of the Russian Federation.

In foreign countries, the process of developing and implementing a construction project is distinguished by regulatory and technical documentation that regulates construction.

In Europe, for the countries of the European Union, developed Eurocodes have been adopted that regulate the design of buildings and construction.

The designation and name of the ten basic Eurocodes is shown in Figure 1.1.

| Designation       | Name                        | Designation       | Name                        |
|-------------------|-----------------------------|-------------------|-----------------------------|
| EN 1990 Eurocode 0| Basis of structural design  | EN 1995 Eurocode 5| Design of timber structures |
| EN 1991 Eurocode 1| Actions on structures       | EN 1996 Eurocode 6| Design of masonry structures|
| EN 1992 Eurocode 2| Design of concrete structures| EN 1997 Eurocode 7| Geotechnical Design         |
| EN 1993 Eurocode 3| Design of steel structures   | EN 1998 Eurocode 8| Design of structures for earthquake resistance|
| EN 1994 Eurocode 4| Design of composite steel and concrete structures | EN 1999 Eurocode 9| Design of aluminium structures|

Fig. 1.1. Designation and name of the Eurocodes

The Eurocodes are divided into ten main sections that cover the basic principles of designing buildings and structures.

The Eurocodes are the common regulatory framework for each EU country. On the basis of this base, each country adopting the Eurocodes at the legislative level must develop its own national standards, taking into account the climatic, seismic, geological and other characteristics of their country.

The Eurocodes contain materials governing the design and construction of empirically tested buildings and structures. However, if it is necessary to develop documentation for a unique structure, it is necessary to develop documentation using laboratory tests and the development of layouts of the future object, followed by the application of loads.

The period of construction (preparation and erection of structural elements of a construction site) is a defining stage in the life cycle for the formation of indicators of the functional quality of construction products. At this stage, violations and/or deviations from the established (design) characteristics, properties and states of individual structural (construction) elements or the building system of an object as a whole can lead to a significant decrease in the indicators of functional and technological reliability, safety and operational efficiency [1,2].

The use of a set of measures within the framework of the program of scientific and technical support of construction characterizes the possibility of carrying out scientific, methodological, organizational and technological, control, and analytical work to identify the actual states of the bearing and enclosing structures being erected.
Scientific and technical support in the format of monitoring the conditions for the formation of building systems is a prerequisite for the construction of capital construction projects characterized by a high level of responsibility (for example, class KS-3) [3].

Methodological substantiation of scientific and technical support for the construction of a building or structure (of any level of responsibility) in the format of monitoring of load-bearing structural elements includes:
- goals, objectives, structure and functions of monitoring the elements of the structural and construction systems of the facility;
- formalized requirements for methods and ways of solving monitoring problems;
- an exact list of supporting structures that are the most important in terms of ensuring the structural, functional, technological, and operational reliability;
- organizational and technological sequence for the creation and maintenance of the monitoring system;
- list of monitored parameters, means of their control and location;
- requirements for technology and regulations for the monitoring of the states of load-bearing structures;
- requirements for the types of resource and technological support for monitoring.

The conditions for the conformity of the monitored parameters reflecting the states of bearing structures during the period of time $t$ (corresponding to the duration of the erection stage) are expressed by an analytical dependence of the form:

$$ f_k(S_1^t, S_2^t, ..., S_n^t; N_1^t, N_2^t, ..., N_m^t; V_1^t, V_2^t, ..., V_m^t) < [\Delta f_k^t] $$

where:
- $f_k$ – function of monitoring the parameters of the states of bearing structures;
- $S_1^t, S_2^t, ..., S_n^t$ – controlled parameters adopted to assess the states of load-bearing structures (for example, indicators of strength or deformability);
- $N_1^t, N_2^t, ..., N_m^t$ – control values of characteristics and parameters of conditions of the internal environment (for example, temperature and humidity of the air in the working area);
- $V_1^t, V_2^t, ..., V_m^t$ – control values of characteristics and parameters of states of the external environment (for example, values of snow or ice load);
- $t$ – duration of the construction period;
- $[\Delta f_k^t]$ – boundary values of the function of monitoring the parameters of the states of load-bearing structures.

It is advisable to monitor the parameters of the technical condition of the bearing structural elements and control the parameters of compliance with the initial design values in automated, permanent and/or periodic modes, depending on the level of responsibility and the organizational and technological sequence of construction [2, 4].

2 Methodological foundations for monitoring the construction of load-bearing structures

Let’s study the application of scientific and technical support of construction of unique high-rise buildings and structures. At the moment, the need for scientific and technical support is reflected in the Russian State Standard GOST 27751-2014 “Reliability of building structures and foundations”, Clause 10.5 says: “For buildings and structures of the KS-3 class with an increased level of responsibility, scientific and technical support should be provided for design, manufacture and installation of structures, as well as their technical monitoring during construction and operation”. In accordance with clause 1 of the Decree of the Government of the Russian Federation of December 26, 2014 N 1521 (as amended
on December 7, 2016) “On approval of the list of national standards and sets of rules (parts of such standards and sets of rules), as a result of which, compliance with requirements of the Federal Law “Technical regulations on the safety of buildings and structures”, GOST 27751-2014 “Reliability of building structures and foundations. Basic provisions”, Sections 1 (clause 1.2), 3, 4 (clauses 4.1, 4.2), 5 (except clause 5.2.6), 6 (except clause 6.1.1), 7-13 (clause as amended, entered into force on October 1, 2015 by the Decree of the Government of the Russian Federation of September 29, 2015 N 1033) is ensured on a mandatory basis. Thus, it can be concluded that the implementation of paragraph 10.5 of GOST 27751-2014 is mandatory and enshrined at the legislative level.

Appendix A of the aforementioned GOST specifies which objects belong to the unique buildings of the KS-3 level of responsibility:

a) buildings and structures of especially dangerous and technically complex objects;
b) all structures, in the design and construction of which fundamentally new design solutions and technologies are used, which have not been tested in the construction and operation practice;
c) objects of life support of cities and settlements;
d) tunnels, pipelines on roads of the highest category or having a length of more than 500 m;
e) construction projects with a height of more than 100 m;
f) span structures of bridges with a span of more than 200 m;
g) large-span shells of construction objects with a span of more than 100 meters;
h) construction projects with cantilever structures over 20 m;
i) construction projects with a buried underground part of more than 15 meters”.

Also, another regulatory document in which you can see the need to apply STS is SP 22.13330.2016 “Foundations of buildings and structures” [3].

In this normative act, it is worth paying attention to clause 4.17: “When designing the bases and foundations of unique buildings and structures or their reconstruction, as well as structures of the 1 level of responsibility, including those being reconstructed, in the conditions of the surrounding buildings, it is necessary to provide for scientific and technical support of construction”. Thus, we can conclude that scientific and technical support of construction starts at the design stage.

In the most general case, an automated system for monitoring the organizational and technological sequence of the production of construction processes and the results of the erection of load-bearing structures implies the formation and organization of the interaction of two structural subsystems for monitoring and assessing the properties and states of elements of the building system [4, 5]:

- subsystem of constant (signal) monitoring: operates in a continuous (including periods of time intended for technological and organizational breaks in construction production) mode. The main functions of the subsystem under consideration include:
  o automatic, real-time monitoring of the parameters of the spatial and technical state of load-bearing structures installed in the design position;
  o automatic, real-time process of forming an information flow of data on manifestations of critical (for spatial and technical safety) changes in the states of load-bearing structures for subsequent transfer to the internal and/or external information environment of the construction industry.

- a subsystem of periodic monitoring: it is included in the work in cases provided for by the regulations (flow chart) of the production of construction processes for the implementation of operational quality control of the construction of load-bearing structures, or when signals are received from the continuous monitoring system. The main functions of the subsystem under consideration include:
o assessment of the safety of the spatial and technical condition of the supporting structures installed in the design position; 
o issuing recommendations for improving or restoring indicators of spatial and technical safety (strengthening, restoration, replacement) of load-bearing structures; 
o monitoring and adjusting (if necessary) the parameters of the constant(signal) monitoring subsystem.

The recommended scope of work on scientific and technical support is also given in BC 22.13330.2016 in clause 4.18 “The scope of work on scientific and technical support of engineering surveys, design and construction of bases, foundations and underground parts of structures should be determined by the general designer and agreed by the construction customer. The scope of work of scientific and technical support may include:
- development of recommendations to the terms of reference and the engineering survey program;
- assessment and analysis of engineering survey materials;
- development of non-standard calculation and analysis methods;
- assessment of geological risks;
- forecast of the state of the bases and foundations of the designed object, taking into account all possible types of impacts;
- geotechnical forecast of the impact of construction on the surrounding buildings, geological environment and ecological situation;
- development of a program of geotechnical and environmental monitoring;
- identification of possible scenarios of emergency situations;
- development of technological regulations for special types of work;
- performance of experimental research work;
- generalization and analysis of the results of all types of geotechnical monitoring, their comparison with the forecast results;
- prompt development of recommendations or correction of design solutions based on geotechnical monitoring data when deviations from the forecast results are detected”.

It can be concluded that during construction, it is necessary to be guided by the developed program for the implementation of STSC. This program, according to SP 22.13330.2016, should be developed by a “specialized organization authorized by the customer”.

Scientific and technical support is mentioned in SP 267.1325800.2016 “High-rise buildings and complexes” [4], in paragraph 3.23. “A set of measures, including scientific, methodological, control, analytical work, carried out to ensure the safety of the construction and operation of a high-rise building and to perform all the functions provided for by the project. Depending on the stage at which it becomes necessary to carry out STS, STS of design and survey work, STS of design, STS of construction, STS of operation, etc. are distinguished”.

The list of the main normative acts in force on the territory of the Russian Federation, which reflect the need to comply with STS, is presented in Figure 1.3.
Fig. 2. Classification of scientific and technical support

It is from this regulatory document that specific stages can be distinguished, which includes scientific and technical support, namely:

- STSE - scientific and technical support of engineering surveys;
- STSD - scientific and technical support of design;
- STSC - scientific and technical support of construction;
- STSO - scientific and technical support at the operation stage.

The classification of scientific and technical support is shown in Figure 3

Fig. 3. Classification of scientific and technical support

In the section of the bases and foundations of SP “Buildings and high-rise complexes”, paragraph 8.1.1.10 describes the work that is recommended to be performed for the organization of STSC when erecting the foundations of high-rise buildings:

“In the process of construction, the following types of work are included in the STS construction works:

- examination of WPP and TR for the performance of geotechnical types of work;
- development of the technology for performing geotechnical works in accordance with the design solution;
- selective quality control of the performance of geotechnical works;
- prompt solution of current tasks arising in the process of performing geotechnical works;
- generalization and analysis of the results of all types of geotechnical monitoring, their comparison with the forecast results;
- prompt development of recommendations or correction of design solutions based on geotechnical monitoring data when deviations from the forecast results are detected”.

The need for scientific and technical support of the design and construction of unique buildings is caused by the complexity of the projects, as well as new structural elements, the design and construction of which is not regulated by modern Russian regulations.

The implementation of scientific and technical support at different stages is ensured by routine measures agreed with the customer.

At the stage of design and survey work:
1.1. Ensuring the completeness and sufficiency of engineering survey results.
1.2. Forecast of geotechnical risks, taking into account all possible types of impacts.
1.3. Consideration in the design of modern structural, technical and technological solutions for the construction of metro facilities, the use of effective and safe materials, construction machines and operational equipment.
1.4. Forecast of the impact of construction on the existing natural and man-made environment.
1.5. Providing a set of measures to minimize the impact of the construction of metro facilities on the existing natural and man-made environment.
1.6. Formation of a set of special technical conditions, enterprise standards and other regulatory and technical documents.
1.7. Certification of new designs and materials.
1.8. Expert and advisory analysis of design documentation in order to eliminate the risks of emergency situations, to improve structural, volume-planning, technological solutions for construction.
1.9. Drawing up a work program for STSC at the construction stage.

At the construction stage:
2.1. Analysis of the results of various types of monitoring and construction quality control data.
2.2. Instrumental support for monitoring and quality control of construction using geophysical and other non-destructive methods.
2.3. Assessment of the serviceability of structures manufactured with deviations from the design.
2.4. Analysis of the causes and consequences (including long-term ones) of emergency situations.
2.5. Making operational decisions, developing recommendations and technical measures to eliminate the consequences of emergencies and negative factors identified in the process of monitoring and quality control, as well as in case of deviation from design solutions.
2.6. Creation and replenishment of an information database based on the results of various types of monitoring and taking this data into account in subsequent design.
2.7. Experimental research work.

Evaluation and decision-making on a critical change in the spatial and technical state of load-bearing structures is carried out using the analytical model (1) by comparing information flows of data on monitored parameters (for example, such parameters as \( S_1, S_2, \ldots, S_n \)) received from sensors of the monitoring subsystems with the values of the criterial values of the function \( \Delta f_k \), corresponding to violations of the established safety parameters in the form of:
− an incident - a state corresponding to the manifestation of the consequences of failure or damage to a structural element that is part of the subsystems for monitoring, or violation of the safety of the spatial and technical state of load-bearing structures installed in the design position;
− an accident - a state corresponding to the onset of a critical for safety spatial and technical state of load-bearing structures or non-pairing of an “incident” state in accordance with the established procedure.

The onset of states of the “incident” and “accident” type is automatically transferred to the external and internal environment for the development and implementation of the necessary management decisions.

3 The results of the implementation of scientific and technical support of construction

The assumption about the possibility (probability) of manifestations of loss of functional quality during the construction of load-bearing structures is a working assessment of the possible manifestation of the law of random events caused by various negative factors.

The mathematical model for assessing or predicting the possibilities of manifestations of deviations in the process of erecting load-bearing structures is focused on taking into account the manifestations of unfavorable factors of the external and internal environment associated with specific features of the organizational and technological sequence of construction processes.

One of the possible areas for the implementation of scientific and technical support of construction is modeling the forecast of possible deviations from the established indicators of the spatial and technical state of load-bearing structures using subsystems of constant and periodic monitoring [6,7].

Figure 1 shows a model (graph) designed to predict the states of load-bearing structures using information data flows coming from sensors of monitoring subsystems.

The categories of states of the form: “norm”, “incident” and “accident” are determined on the basis of measurement data by monitoring subsystems and are taken as basic states in assessing (forecasting) the quality and safety of load-bearing structures when they are installed in the design position.

\[
\begin{align*}
\lambda & \text{ – a quantitative parameter characterizing the direction of the transition of the load-bearing structure from a state of less significant hazard to a more hazardous state. For example, } \lambda (1 \rightarrow 2) \text{ is the direction of the transition: from the initial state: \textit{“State 1 (norm)”} to the final state: \textit{“State 2 (incident)”};} \\
\mu & \text{ – a quantitative parameter characterizing the direction of the transition of the load-bearing structure from a more significant hazardous state to a less hazardous state. For}
\end{align*}
\]

Fig. 4. Graph (model) for the analysis of the spatial and technical states of load-bearing structures
example, \( \mu \) (2→1) is the direction of the transition: from the initial state: “State 2 (incident)” to the final state: “State 1 (normal)".

The states of the mathematical model adopted for the analysis of the parameters of the properties of load-bearing structures are characterized as:

- expected (established by the project) indicators of deviations (normal quality of load-bearing structures) - State 1, “norm”;
- minor deviations (from those established by the project) indicators (permissible quality of load-bearing structures) - State 2, “incident”;
- regular (systemic) deviations (from those established by the project) indicators (critical quality of load-bearing structures) - State 3, “accident”.

Information on the quantitative values of such parameters as \( \lambda \) and \( \mu \) is made up of measurement flows generated by the subsystems for monitoring the state of load-bearing structures.

If we assume the probabilistic nature of the states of supporting structures, then a quantitative forecast of possible changes and deviations from the established quality and safety indicators can be displayed in the format of a mathematical model (Figure 4) and the corresponding system of differential equations:

\[
\begin{align*}
- (\lambda_{1 \rightarrow 2} + \lambda_{1 \rightarrow 3}) \cdot P_{1}(t) + \mu_{2 \rightarrow 1} \cdot P_{2}(t) + \mu_{3 \rightarrow 1} \cdot P_{3}(t) &= P'_{1}(t); \\
- (\lambda_{2 \rightarrow 3} + \mu_{2 \rightarrow 1}) \cdot P_{2}(t) + \lambda_{1 \rightarrow 2} \cdot P_{1}(t) + \mu_{3 \rightarrow 2} \cdot P_{3}(t) &= P'_{2}(t); \\
- (\mu_{3 \rightarrow 1} + \mu_{3 \rightarrow 2}) \cdot P_{3}(t) + \lambda_{1 \rightarrow 3} \cdot P_{1}(t) + \lambda_{2 \rightarrow 3} \cdot P_{2}(t) &= P'_{3}(t);
\end{align*}
\]

(2)

where:

\( P_{1}(t), P_{2}(t), P_{3}(t) \) – the probability of the state of load-bearing structures in the accepted categories: “norm”, “incident”, “accident”, respectively.

\( P'_{1}(t), P'_{2}(t), P'_{3}(t) \) – the probability of a change (transition) of the state of load-bearing structures into the category of states “norm”, “incident”, “accident”, respectively.

\( t \) – time period corresponding to the duration of the erection of load-bearing structures.

For practical studies of the features of the operational state and functioning of load-bearing structures after their construction (taking into account the presence of deviations from the initial design solutions), the composition of the predictive mathematical model (see Figure 4 and system of differential equations (2)) can be expanded by introducing additional categories that most accurately characterize the features of functional properties and states.

4 Discussion and conclusion

Monitoring of the parameters of the technical state of load-bearing structures allows not only based on experience (a posteriori), but also predictive analysis of the behavior of load-bearing structures.

As a result of the study, a system was developed for the formation of organizational and technical measures within the framework of scientific and technical support during the construction of high-rise buildings and structures.

The analysis of the regulatory documents of the Russian Federation, which reflects the need for scientific and technical support of construction, is carried out. The foreign legal regulation of the building construction process is considered.

The result of the work was a developed parametric model for assessing the efficiency of the application of the scientific and technical support system for the construction of unique high-rise buildings.
A quantitative assessment (forecast) of the probability of states, obtained using actual and verified measurement data, contributes to the development and implementation of timely and effective solutions aimed at countering the consequences of unfavorable factors during the construction of load-bearing structures.

References

1. V.I. Stankevich, L.H. Shackaja, Obespechenie nadezhnosti ieksplyuatacionnoj bezopasnosti zdanij i sooruzhenij nachinaetsja s proekta, Promyshlennoe i grazhdanskoe stroitel'stvo, 9, 51–53.57 (2001).

2. V.N. Dubenjuk, Formirovanie organizacionno-jeconomiceskogo mehanizma povyshenija kachestva, Snizhenija stoimosti i sokrashhenija srokov stroitel'stva obyektov: dissertacija na soiskanie uchjonoj stepeni kandidata jeconomiceskikh nauk: 08.00.05, DubenjukVladimirNikolaevich, SPb, 2012, 155 p.

3. GOST 27751-2014, Nadezhnost' stroitel'nyh konstrukcij i osnovanj, Osnovnye polozhenija (Moscow, Standartinform, 2015).

4. MRDS 02-08, Posobie po tehicheskomu soprovozhdeniju i monitoring strojashshhsja zdanij i sooruzhenij, v tom chisel bol'sheproletnych, vysotnych i unikal'nych (Rosstroj, Moscow, 2008).

5. Metodika monitoring sostojania nesushhih konstrukcij zdanij i sooruzhenij. Obshhiepolozhenija (MChSRF, Moscow, 2008).

6. O.L. Smirnov, Sostavlenie i optimizacija modelej slozhnyh system (LAP LAMBERT Academic Publishing, Moscow, 2018).

7. A.A. Samarskij, A.P. Mihajlov, Matematichesko modelirovanie: Idei. Metody. Primery (Fizmatlit, Moscow, 2001).