DIGITAL TWINS OF THE STRESS-STRAIN STATE FOR AUTOMATED MONITORING OF HYDRAULIC STRUCTURES

A. N. Simutin,[1] I. D. Arsen'ev,[2] E. A. Khoteev,[3] and A. V. Deineko[4]

The main direction in the development of monitoring (field observations) of hydraulic structures (HSs) is automation with transition to continuous monitoring of stress-strain state (SSS) by means of automated telemetry control and measuring equipment. In this regard, it becomes possible to automate the assessment of the technical conditions of an HS, considering changes in loads and impacts using a digital twin (DT) of the HS SSS, which is developed via machine learning based on automated monitoring data. The DT represents a finite element model of an HS that is consistent with monitoring data. The development of DTs requires automated monitoring of vertical displacement. This study discusses a technique of developing DTs using the Russian-made digital sensors of the hydrostatic leveling device "Monitron" and a Russian-made cloud-based information and diagnostic monitoring system.

Keywords: digital twin (DT); finite element method (FEM); automated monitoring; hydrostatic leveling.

The main field in the development of monitoring (field observations) of hydraulic structures (HSs) [1] is automation with transition to continuous monitoring of stress-strain state (SSS) via automated telemetry control and measuring equipment (CME). With this approach, monitoring should be performed on a round-the-clock basis, in real time, without constant human participation.

However, the complexity is represented by intellectualization of the automated assessment of the HS technical condition. Currently, use of a simple algorithm for comparing CME readings with fixed safety criteria (SC) prevails. However, this approach does not consider the dynamics of changes in the state of actual HS facilities and does not benefit from the availability of a large amount of measurement results data (big data) generated by an automated telemetry CME.

Improving the method of automated assessment of the HS technical condition requires the inclusion of the digital twin of the HS SSS (hereinafter referred to as DT) in the monitoring system (see Fig. 1), which is developed based on monitoring data using modern data analysis methods (data science), particularly machine learning.

The following work presents the technology for using the DT jointly developed by Monitron and Sigma Tau on the basis of data from Russian-made digital sensors of a hydrostatic leveling device using Russian-made cloud IT solutions; this technology ensures the operation of the DT in a standard Internet browser environment in any operating system (including Russian-made ones) without having to use specialized programs from the field of mathematical modeling. Delivery, installation, maintenance, and 24-h technical support of this technology is provided by GeoSpecStroj.

What is a DT? A DT is a computer model that accurately reproduces a real HS's response to changes in loads, impacts, and operating conditions (for example, changes in water level in a reservoir, seasonal temperature fluctuations, and opening, and closing of gates). It is based on the finite element method (FEM) and is designed to calculate settlements and other SSS parameters of a real HS while considering the results of the structure's monitoring.
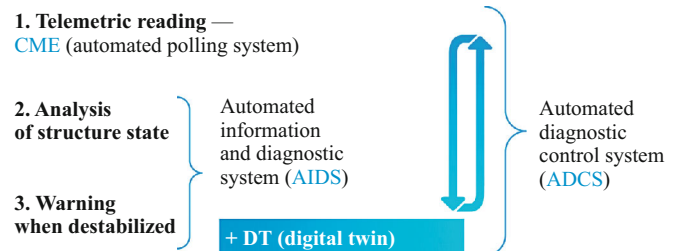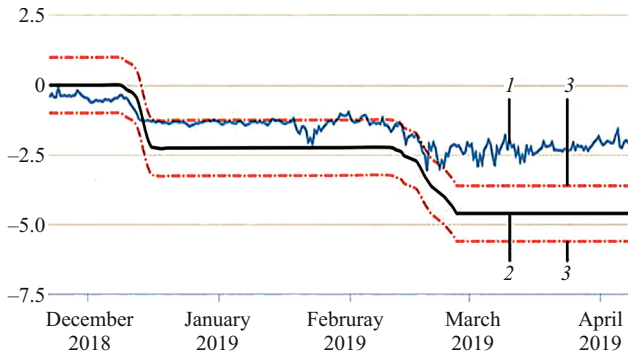

Fig. 1. Structure of the HS monitoring system. Also see the DT connection diagram.

[1] "Monitron" LLC, Russia; e-mail: simutin@sigma-tau.xyz.
[2] "GeoSpecStroj" JSC, Russia.
[3] "Sigma Tau" LLC, Russia.
[4] "Sigma Tau" LLC, Russia; e-mail: deyneko@sigma-tau.xyz

Fig. 2. Field (*1*) and calculated (*2*) vertical displacements, as well as the predicted corridor of calculated values (*3*) in the case of heading of two tunnels under the lock.

Noteworthily, the concept of DT is intersectoral in nature and is part of the concept of digitalization and the fourth industrial revolution. Digitalization is a transition to fundamentally novel methods of work based on information technology.

An example of digitalization is the transition to building information modeling (BIM) or information modeling technologies, as well as product lifecycle management. Models of three-dimensional (3D) (3D information model), 4D (3D information model considering the stages of construction), 5D (considering logistics and financial flows during the construction period), 6D (continuing action for the period of operation) classes are being introduced. One of the main tasks of 6D models is monitoring support.

The introduction of the DT, along with BIM models, pertains to digitalization of the design, construction, and operation of HSs, and is aimed at creating new professional opportunities.

A DT is based on a common scientific and methodological base, together with SSS calculation models, which are developed at the design stage. Differences are determined by different tasks.

Design calculation models reproduce the limiting states of a facility under worst combinations of loads and impacts, while "reserve" errors are often allowed, which enables to simplify calculations and reduce corresponding labor costs.

The tasks and possibilities of a DT are discussed in the following.

Apparently, a DT must reproduce the actual state of a structure. Therefore, we must consider the history of operation of a specific HS and its actual condition vis-a-vis defects, damage, and actual deformations; real properties of building materials and foundation soils (these differ from the designed ones established according to design standards with a margin for natural variability of material properties); actual loads and impacts recorded during the monitoring of a real structure (rather than artificially compiled most unfavorable combinations of loads and impacts specified during design works); nonlinear operation of the structure (combination of genetic, constructive, physical, and geometric nonlinearity);

and connectivity of the physical processes of the facility operation (SSS, heat exchange, and filtration).

The method of considering certain aspects is specified depending on specific tasks assigned to the DT.

From the above discussion, it follows that development of a DT requires considering not only initial data of a project but also subsequent data accumulated during construction and operation during monitoring of the structure.

Tasks of a DT. A DT is used in the monitoring process for ensuring timely notification of the occurrence of destructive processes, which ensures prevention of accidents, reduction in the cost of repairing damage to the structure owing to early detection, financial and economic benefits (such as reducing insurance costs owing to risk reduction), and cost optimization for preventive maintenance overhaul.

A typical application of a DT involves multiple modeling of the actual state of a structure by adding new calculation stages to the model, which consider changes in loads and impacts over time.

The CME readings are compared with the DT calculation results. Correspondence of the results implies that the real structure remains consistent with the model, which means that the nature of the structure operation does not change, and that its technical condition is stable.

Thus, the DT reveals destructive processes by means of indirect signs owing to their influence on the SSS parameters, primarily on the vertical movements and tilts of the structure, which are amenable to automated control in real time.

This enables for detection of many destructive processes included in typical scenarios of HS accidents, such as foundation suffusion, impervious curtain discontinuity, concrete cracking, opening of working joints in concreting, and corrosion of reinforcement of retaining walls and other structures.

The DT can be used set to individually, for each CME tool, the predictive corridor of the parameter observed, i.e., the calculated value of the parameter adjusted for error of engineering calculations and field measurements (see Fig. 2). The predictive corridor changes over the course of calendar time owing to changes in loads, impacts, and operating conditions.

This enables for detection of destructive processes earlier than that in the case of the traditional safety criteria (SC), which increases the time reserve for the implementation of measures to prevent a possible accident.

The disadvantage of SC systems is that they cannot predict the dynamics of changes in the technical condition of a structure. Until the SC are violated, the structure is considered operational, even if there exists an SC violation tendency/possibility in future.

The advantage offered by a DT consists in the ability to analyze the dynamics of changes in SSS parameters. For example, let us consider a situation in which vertical displacements decrease (a rise occurs) according to monitoring data [11, 12], but let us also consider that they should increase ac-
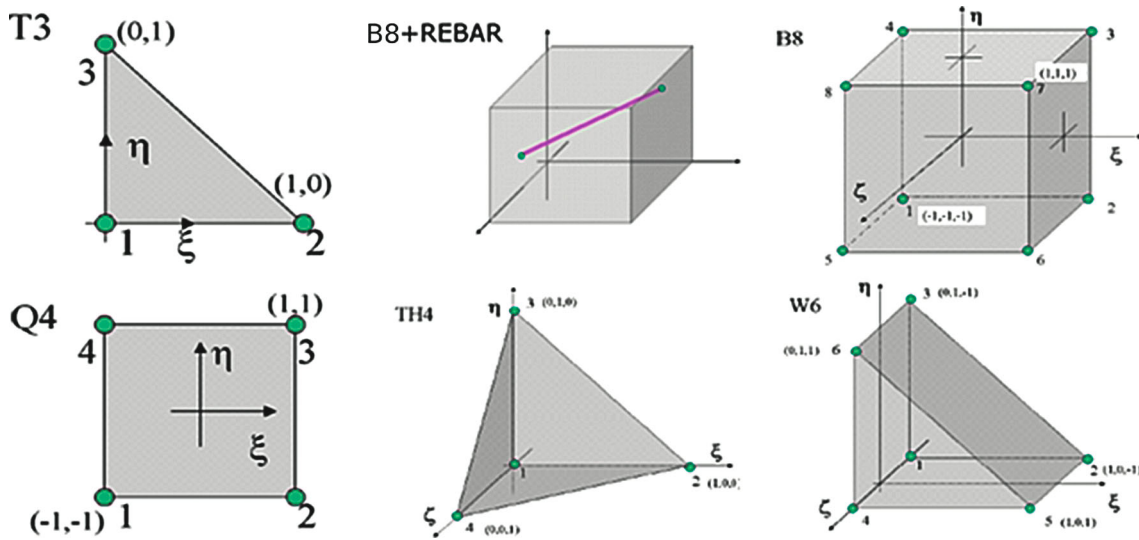
Fig. 3. Finite element (FE) of the first order (counterclockwise enumeration): triangular, quadrangular, quadrangular tetrahedron, hexagonal prism, octagonal hexahedron, combined finite element (FE) of a volume hexahedron, and a 3D rod.
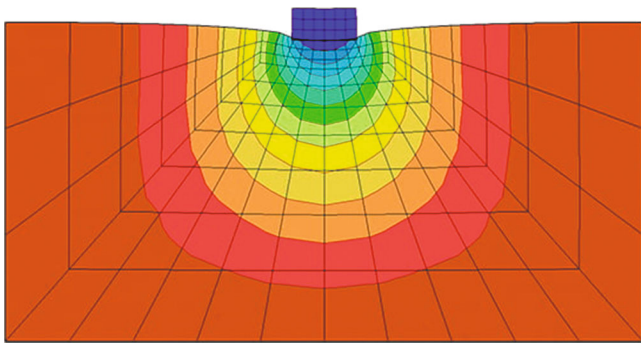

Fig. 4. Typical mesh topology with variable FE size.

Fig. 5. FEM model of a DT at the intersection of hydraulic engineering and transport construction: heading of two metro tunnels with 6 m diameter under the Karamyshevsky lock (Moscow).

cording to DT data. Such an case may indicate breakthrough of the impervious curtain and increase in back pressure.

The usage value of a DT consists in early detection of destructive processes. Changes in acting loads and influences constantly occur (e.g., seasonal temperature fluctuations). This interferes with the usual methods of engineering analysis; however, a DT controls the structure stability irrespective of changes in loads and impacts because these changes are considered using a mathematical model. Thus, a DT answers the question if changes in the SSS parameters are adequate to changes in loads on the one hand and those in impacts on the other hand?

The results of a DT operation are interpreted as follows.

If the monitoring data fit into the forecast corridor, then

— the real structure corresponds to its mathematical model,

— the technical condition of the structure is stable, and

— destructive processes do not develop.

If the monitoring data are beyond the predictive corridor, the structure ceases to correspond to its mathematical model,
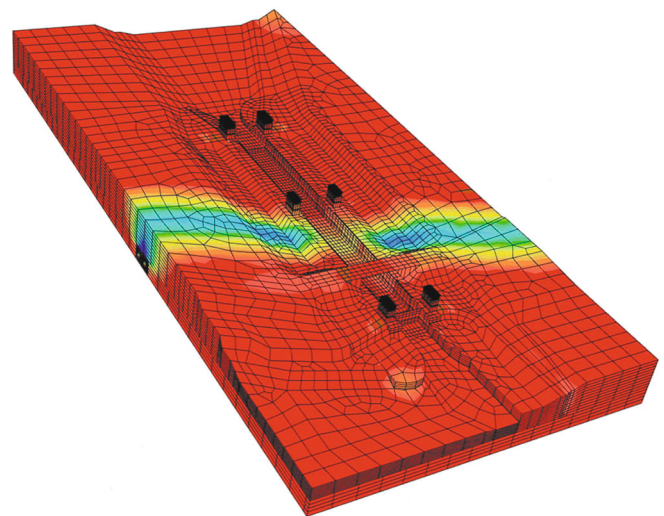
and the state of the structure is possibly in the process of changing.

Mathematical apparatus of DTs. FEM [2 – 5] is the most common method of mathematical modeling of hydraulic engineering and other building structures.

A finite element (FE) model represents a geometric model of a structure, approximated using small areas of an elementary form, namely FEs (see Fig. 3), which are interconnected at the nodes of the FE mesh. Additional nodes can be added on the FE edges, which allow for obtaining an FE of the second order.

The dimensions of FEs are selected so as to approximate the fields of the results (displacements, deformations, and

stresses). Therefore, the FE dimensions are usually changed according to the expected change in the result fields (see Fig. 4) to reduce the total number of FEs. FE mesh optimization is important for DTs, which are designed to be calculated multiple times as loads and actions change, thereby generating a large amount of data.

FEM allows for reproduction of arbitrarily complex computational schemes in the formulation of "structure – foundation" in any branch of the construction industry, as well as at the intersection of the fields (see Figs. 5 and 6).

To create a DT, one must consider various aspects of HS operation and, accordingly, several types of FEM modeling [6, 7].

Strength FEM modeling is used to determine the SSS parameters of a structure and foundation. Initial data for the strength FE model are physical and mechanical characteristics of the building materials and soils; there are physical characteristics (density, coefficient of linear expansion, among others), mechanical characteristics (strain modulus, Poisson's ratio, among others), strength characteristics (ultimate stress of concrete, angle of internal friction of the soil, among others); boundary conditions (BCs) of the first kind, namely specified displacements, and rotations of nodes, which can be zero (support fastenings) or nonzero (kinematic

BCs); BCs of the second kind, namely specified forces and moments (concentrated or distributed loads, gravity, and hydrostatic weighing); BCs of the third kind, namely the relationship between displacements and forces (elastic supports, among others); and specified deformations and stresses (thermal expansion, shrinkage, compensatory injection, and preliminary, and subsequent reinforcement stress).

Computer calculation represents a solution of the basic FEM equation, which is expressed using a system of linear algebraic equations (SLAE) and is presented in the matrix form:

$$[K]\{u\} = \{p\}, \qquad (1)$$

where $[K]$ represents the stiffness matrix, which is a computer representation of the FE mesh and material properties; $\{u\}$ the column vector of node displacements; and $\{p\}$ the column vector of external forces applied to the nodes.

The dimension of the SLAE is determined by the number of degrees of freedom. When modeling in a 3D formulation of soil and massive concrete, each node has three degrees of freedom (displacements along the X, Y, and Z coordinate axes). However, when modeling bending structures (beams, slabs), each node has six degrees of freedom (displacements along three axes and rotations around three axes).

$$
\begin{vmatrix}
K_{11} & K_{12} & K_{13} & K_{14} & K_{15} & K_{16} & K_{17} & K_{18} & K_{19} & K_{110} & K_{111} & K_{112} \\
K_{21} & K_{22} & K_{23} & K_{24} & K_{25} & K_{26} & K_{27} & K_{28} & K_{29} & K_{210} & K_{211} & K_{212} \\
K_{31} & K_{32} & K_{33} & K_{34} & K_{35} & K_{36} & K_{37} & K_{38} & K_{39} & K_{310} & K_{311} & K_{312} \\
K_{41} & K_{42} & K_{43} & K_{44} & K_{45} & K_{46} & K_{47} & K_{48} & K_{49} & K_{410} & K_{411} & K_{412} \\
K_{51} & K_{52} & K_{53} & K_{54} & K_{55} & K_{56} & K_{57} & K_{58} & K_{59} & K_{510} & K_{511} & K_{512} \\
K_{61} & K_{62} & K_{63} & K_{64} & K_{65} & K_{66} & K_{67} & K_{68} & K_{69} & K_{610} & K_{611} & K_{612} \\
K_{71} & K_{72} & K_{73} & K_{74} & K_{75} & K_{76} & K_{77} & K_{78} & K_{79} & K_{710} & K_{711} & K_{712} \\
K_{81} & K_{82} & K_{83} & K_{84} & K_{85} & K_{86} & K_{87} & K_{88} & K_{89} & K_{810} & K_{811} & K_{812} \\
K_{91} & K_{92} & K_{93} & K_{94} & K_{95} & K_{96} & K_{97} & K_{98} & K_{99} & K_{910} & K_{911} & K_{912} \\
K_{101} & K_{102} & K_{103} & K_{104} & K_{105} & K_{106} & K_{107} & K_{108} & K_{109} & K_{1010} & K_{1011} & K_{1012} \\
K_{111} & K_{112} & K_{113} & K_{114} & K_{115} & K_{116} & K_{117} & K_{118} & K_{119} & K_{1110} & K_{1111} & K_{1112} \\
K_{121} & K_{122} & K_{123} & K_{124} & K_{125} & K_{126} & K_{127} & K_{128} & K_{129} & K_{1210} & K_{1211} & K_{1212}
\end{vmatrix}
\times
\begin{vmatrix}
u_{1(1x)} \\
u_{2(1y)} \\
u_{3(1z)} \\
u_{4(1rotx)} \\
u_{5(1roty)} \\
u_{6(1rotz)} \\
u_{7(2x)} \\
u_{8(2y)} \\
u_{9(2z)} \\
u_{10(2rotx)} \\
u_{11(2roty)} \\
u_{12(2rotz)}
\end{vmatrix}
=
\begin{vmatrix}
p_{1(1x)} \\
p_{2(1y)} \\
p_{3(1z)} \\
p_{4(1rotx)} \\
p_{5(1roty)} \\
p_{6(1rotz)} \\
p_{7(2x)} \\
p_{8(2y)} \\
p_{9(2z)} \\
p_{10(2rotx)} \\
p_{11(2roty)} \\
p_{12(2rotz)}
\end{vmatrix}, \qquad (2)
$$

where K_{ij} represents the stiffness matrix elements (i denotes the line index and j the column index), u_i the displacement of nodes in the direction of the degree of freedom under the serial number i, and p_i the external forces or supporting reactions applied according to the degree of freedom under the ordinal number i; ($1x$) — numbers of nodes from 1 to 3 corresponding to each degree of freedom and directions along the X or Y axes are given in brackets.

For example, for a beam FE of the first order (for 2 nodes and 6 degrees of freedom in each node, the number of degrees of freedom is $2 \times 6 = 12$, and the dimension of the stiffness matrix is 12×12 [Eq. (2)].

The stiffness matrix element K_{ij} is numerically equal to the reactive force originating in the ith direction from a unit displacement in the jth direction. For example, K_{47} equals the moment p_4 (the moment at node 1 around the X axis) caused by the unit displacement u_7 (at node 2 in the X direction).

Thus, all loads and impacts in the course of computer simulation are converted into a combination of given external forces applied to the nodes and given displacements of the nodes (including zero displacements, support fastenings).

In the course of computer calculation, the results associated with the mesh nodes, i.e., movements and supporting reactions, are initially determined. Furthermore, according to
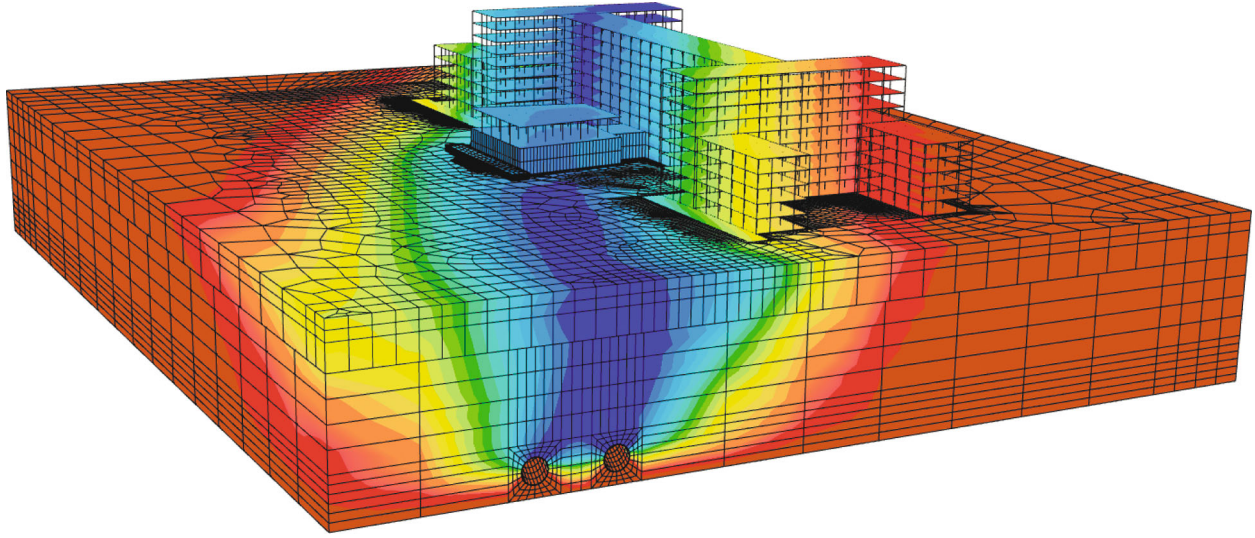
Fig. 6. FEM model of the DT at the intersection of transport and civil engineering: heading of two metro tunnels with 6 m diameter under the building of the I. M. Gubkin Russian State University of Oil and Gas (Moscow).

the algorithms of FEM, the results distributed in the volume of FEs are calculated, namely deformations, stresses, and other necessary SSS parameters.

In terms of time, FE models are considered in stationary and nonstationary formulations, which correspond to statics, and dynamics, respectively, within the strength modeling.

In statics, the deformation rate of the model is assumed to be infinitely low; therefore, the inertial force in the node is equivalent to the force of gravity and is constant in time. The time scale in a stepwise static calculation indicates the sequence of model transformation stages; the duration of the time intervals between the stages is of no importance. It is in the static formulation according to Eq. (1) that the majority of strength calculations are performed, and most of the DTs function in the field of hydraulic engineering.

In dynamics, we consider not only movements but also the time during which these movements occur. Velocity and acceleration are introduced in Eq. (1)

$$[M] \cdot \{\ddot{u}\} + [C] \cdot \{\dot{u}\} + [K] \cdot \{u\} = \{p\}, \qquad (3)$$

where $[M]$ represents the mass matrix, $\{\ddot{u}\}$ the column vector of node accelerations, $[C]$ the damping matrix, and $\{\dot{u}\}$ a column vector of node velocities.

The time scale in the dynamic calculation corresponds to the physical time. The state of rest is usually taken as the initial conditions.

Dynamics is considered in the implicit and explicit formulations.

In implicit dynamics, the rate of propagation of mechanical interaction in the volume of the FE model is assumed to be infinitely high. The force applied at a certain point of time begins to instantly affect all nodes. Therefore, the equilibrium condition is satisfied: the sum of all forces and moments at any time is zero. In this case, displacements, veloci-

ties, and accelerations in each node begin to change in time depending on the distribution of stiffness, damping, and masses, for example, in the form of an oscillatory motion.

Calculations of HSs for seismic and vibrational impacts are performed to formulate implicit dynamics. The time step is determined using the characteristic frequencies of the structure's natural oscillations.

Explicit dynamics considers the propagation velocity of mechanical interaction, which equals the propagation velocity of elastic waves (speed of sound) in the simulated medium (soil, concrete). The force applied at a certain moment of time begins to affect other nodes with a delay due to the time of passage of the elastic wave to the point considered. The equilibrium condition is not applied because the sum of all forces and moments at any given time is not necessarily zero in this case.

For formulation of explicit dynamics, HS calculations are performed for actions involving rapid impacts, for example, collision with an aircraft. The time step is determined using the time taken by the elastic wave to pass through the FE.

Heat transfer simulation is used to reproduce the temperature field in a structure and foundation. The following are the initial data for the FEM model of heat transfer:

— physical characteristics of materials (thermal conductivity, density, and specific heat capacity);

— BCs of the first kind (predetermined temperatures);

— BCs of the second kind, namely heat flows (for example, amount of heat released during the exothermic reaction of concrete hardening);

— BCs of the third kind are heat fluxes that depend on temperature (for example, conditions of convection, or radiant heating on the structure surface in contact with air).

Computer calculation is performed according to Eq. (1) with the difference that temperatures are considered rather than $\{u\}$, and that heat fluxes are considered rather than $\{p\}$.

The calculation can be performed in stationary and nonstationary formulations.

The stationary formulation involves the determination of a steady (constant in time) temperature field, for example, calculation of heat losses through building envelopes using a calculated temperature difference.

The nonstationary formulation reproduces the change in temperature field over time, for example, in the massive concrete of a dam under seasonal temperature influence.

The seasonal temperature regime constantly changes; therefore, initial conditions cannot be established by means of a stationary calculation. Consequently, the nonstationary calculation starts with average annual temperature, following which the calculation is performed for several years until the formation of a temperature regime that coincides with the monitoring data.

A typical difficulty in modeling of actual heat transfer is the insufficient equipment of the monitoring system, in which the air temperature is often measured but solar radiation is not measured (actinometric observations), which also affects the HS temperature regime.

Heat transfer calculation is usually required to determine the temperature field in concrete structures in a bid to consider the thermal expansion of concrete.

Filtration modeling is used to determine the parameters of water saturation and water movement in a structure and foundation. Initial data for the filtration FEM model are filtration characteristics of materials (filtration coefficient, porosity, and residual water saturation coefficient), BCs of the first kind (namely water pressure, for example, pressure on the bottom of a reservoir), BCs of the second kind (namely seepage discharge, for example, dewatering with a fixed pumping flow), and BCs of the third kind (namely consumption that depends on pressure, for example, seepage surface).

Computer calculation is performed according to Eq. (1) with the difference that pressures are considered rather than $\{u\}$, and that seepage discharge is considered rather than $\{p\}$. Stationary and nonstationary formulations of filtration calculations are considered in a similar manner.

The stationary formulation involves the determination of a steady (constant with time) filtration regime, for example, filtration under a dam at a constant level of upstream and downstream pools.

The nonstationary formulation considers the rate of change in the filtration regime over time, for example, time required for the depression surface to be submerged after start of dewatering.

For a nonstationary calculation, we must determine initial conditions, which are usually the results of a stationary calculation for the filtration regime registered over a long period of time.

Filtration calculation allows for obtaining the following types of results:

— calculation of counterpressure on the dam base and the pressure of flooded soils on the retaining structures;

— determination of the position of depression surface (calculation of rise in groundwater level from the damming effect, prevention of seepage on the downstream face of the dam);

— testing the filtration stability of foundations and soil structures (the filtration rate must be below the permissible level);

— calculation of drainage consumptions.

Connected (multiphysics) modeling is the joint application of several types of modeling to solve a common problem. In this case, the results of one type of simulation are used as initial data for another type of simulation. For example, according to the results of the heat transfer calculation, in winter, the cooling of concrete on the downstream face of the dam decreases the concrete volume in the strength problem. If the concrete-free deformation is limited (the case of a statically indeterminate problem), the tensile stresses will increase and may cause cracking and opening of the joints.

A connected FEM model can have either one FE mesh, which is used for all types of modeling, or several meshes intended for different types of modeling. Using several meshes is advisable in the case of contradictions between the types of modeling vis-a-vis the requirements for the density of the FE mesh in different regions of the model.

Some types of connected calculations have special terms:

— two-phase calculation is a connected calculation of strength and filtration;

— calculation of a thermally stressed state or that of thermoelasticity is a connected calculation of strength and heat transfer;

— heat- and mass-transfer calculation is a connected calculation of filtration and heat transfer.

For example, to develop a DT for a section of a high concrete dam, a coupled model is usually required, namely that of strength in a static nonlinear setting, nonstationary heat transfer, and nonstationary filtration.

Nonlinearity is a phenomenon that arises when the response of a structure (displacement, deformation, stress) is not directly proportional to loads and impacts. This implies that the structure's properties are not constant and, in turn, depend on loads, and influences. Considering this decisively influences the computer simulation accuracy.

Types of nonlinearity can be genetic (modeling the stages of construction of a structure and the application of loads and influences), constructive (modeling the interaction of the structure parts with each other, for example, opening and displacement along the contact of the structure with the base), physical (change in the strength and deformation properties of materials depending on stress state), and geometric (effect of structure deformation on SSS calculation).

Within the framework of computer simulation, the concept of engineering nonlinearity arises, which is methods of indirect modeling of nonlinearity, for example, lowering the deformation modulus of reinforced concrete to simulate cracking.

Considering that various nonlinearity types considerably increase the reliability of computer simulation, development of DT is of great importance.

Machine learning of a DT. A DT is developed based on the following principles:

— realistic simulation that involves modeling an actual HS rather than its idealized design, and actual operating conditions rather than the design combinations of loads and impacts provided for the structure;

— machine learning by a mathematical model based on monitoring data of a real structure.

Machine learning is a generalized name for methods whose characteristic attribute is refinement of a mathematical model on the basis of its application to initial data, for which the simulation result is known a priori. Such a statement of the problem exactly corresponds to monitoring, as it is known what CME readings are registered in a specific state of the structure at a present moment and in the past.

The parameters of the FE model have a strict physical importance and clear limits of possible values; however, the actual values of many parameters, such as deformation moduli, filtration coefficients, or back pressure on the dam foot, are not exactly known. In this case, the mathematical model is calibrated. It is determined from engineering considerations which parameters can be refined and within what limits their variation is possible. Furthermore, we use multivariate calculations to select such values of the variable parameters, at which the FE model calculation results coincide with the monitoring data.

For example, when refining the three deformation moduli, we obtain the following:

$$E_1 = [e_{1min} \ldots e_{1max}], \quad E_2 = [e_{2min} \ldots e_{2max}],$$

$$E_3 = [e_{3min} \ldots e_{3max}],$$

where E_i represent the unknown, desired deformation moduli, and e the values of the deformation moduli from the variation interval.

When the calculated data coincide with the field data, the selection of a combination of the modules E_1, E_2, and E_3 is extremely resource intensive. If we consider five options for each module, we must then perform $5^3 = 125$ calculations of the FE model, while with 10 options, $10^3 = 1000$ calculations are required.

For acceleration, the mathematical experimental design theory is used. Rather than enumeration of the entire set of possible combinations of e_1, e_2, and e_3, the minimum number of combinations is selected, sufficient to construct a response function of a predetermined type, which connects the variable parameters with the calculation result:

$$F(e_1, e_2, e_3) = R,$$

where $F(e_1, e_2, e_3)$ represents the response function and R the calculation result expressing the discrepancy between the calculated and natural settlements.

The essence of the response function consists in the fact that to obtain the result R with a certain combination of variable modules (e_1, e_2, e_3), it is sufficient to perform response function computation rather than FE model calculations.

A linear or quadratic polynomial is used as a response function, which, with three varied parameters, is expressed as follows:

$$F^{(1)}(x_1, x_2, x_3) = b_0 + b_1 e_1 + b_2 e_2 + b_3 e_3 +$$

$$+ b_4 e_1 e_2 + b_5 e_1 e_3 + b_6 e_2 e_3,$$

$$F^{(2)}(x_1, x_2, x_3) = b_0 + b_1 e_1 + b_2 e_2 + b_3 e_3 +$$

$$+ b_4 e_1 e_2 + b_5 \cdot e_1 \cdot e_3 + b_6 e_2 e_3 + b_7 e_1^2 + b_8 e_2^2 + b_9 e_3^2,$$

where b represent the regression coefficients calculated using the least squares method.

The required number of combinations of variable parameters to construct the response function is determined via the experimental plan (see Table 1).

Furthermore, we use the methods of mathematical analysis of the response function to determine a combination of variable parameters, for which the calculated and field data coincide:

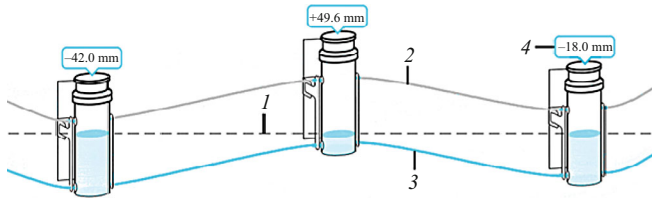$$(E_1, E_2, E_3) = \arg \min F(e_1, e_2, e_3).$$

A similar approach is applied to any parameters of the FE model, such as material properties, fracture configurations, and layering of engineering geological elements, among others.

Development of a DT based on automated settlement monitoring data. CME is used to control a limited number of SSS parameters in a limited number of points of the structure; therefore, the task of the monitoring project is the selection of an optimal combination of instruments (see Table 2) and number of measuring points.

Per the Saint-Venant principle, uneven distribution of stresses, and strains rapidly decreases with increase in distance from local sources of unevenness. This principle is particularly relevant for hydraulic concrete, which is characterized by large thickness and massiveness, which, due to

TABLE 1. Combining Parameters to Plot a Quadratic Function of Response

Number of parameters	Number of parameter combinations		
	Box – Behnken design	Box – Wilson design	Total of possible combinations
2	—	9	9
3	13	15	27
4	25	25	81
5	41	43	243
6	61	77	729
7	85	143	2187

Fig. 7. Operation principle of the hydrostatic leveling system: *1* — working fluid level in the hydraulic system; *2* — air route hose; *3* — hydraulic route hose; *4* — change in height position of the measuring vessel from the initial one.

cracking, possesses pronounced local heterogeneity, and anisotropy.

Therefore, for the development of a DT, the most informative parameters are those that characterize the operation of the structure as a whole, compared with the parameters that locally characterize the operation of the structure at the measurement point. Per Table 2, the operation of the entire structure is characterized by means of displacement measurements, and the local operation at the measurement points is characterized by means of stress and relative strain indicators.

For dams, due to the SSS nature, loads, and impacts, settlement (vertical displacement) is the main type of displacement for assessing the structure's state.

Settlement lends itself well to automated measurement in real time using hydrostatic leveling technology, based on the creation of a system of communicating vessels inside which the working fluid level has an equal elevation (see Fig. 7).

The technical characteristics of automated hydrostatic leveling systems for construction purposes accepted in international practice were completely observed during the development of the latest Russian-made digital sensors of the hydrostatic leveling device "Monitron" [8]. The key innovation was the development of a Russian-made optical-electronic system for detection of liquid level inside the measuring vessel. This provided a considerable reduction (up to 10 times) in the cost of measuring equipment compared with international analogs, which use expensive precision string transducers or helical electromechanical liquid level sensors developed in the last century.

Russian-made sensors of the hydrostatic leveling device digital DGC-19 possess ±0.05 mm accuracy of taking readings and 100 mm measurement range with a repeating pattern of 1 time per minute. The sensors are produced universal with an extended operating temperature range from –65 to +50°C, with a high degree of protection, i.e., IP 66 (dust proof, protected from strong water jets) with a basic service life of 15 years. The sensors are manufactured with a modern design and can be disguised as architectural lighting devices.

The sensor DGC-19 is included in the State Register of Measuring Instruments (State Register of MI) [9]. There are prices MRR-3.10–20 for use of sensors for automated geotechnical monitoring [10].

The DGC-22 model with an additional inclinometer function (measurement of angles of rotation to the horizon) is in the testing stage.

The leveling process does not depend on weather and climatic conditions owing to the physical principle of measurements; there is no need for direct visibility between the sensors. This, combined with high measurement time interval, ensures the highest reliability, and continuity of settlement monitoring throughout the structure's life cycle.

Ever since 2014, experience has been gained in the use of "Monitron" sensors at dozens of facilities in Russia and other countries [11 – 16], particularly in hydrotechnical construction, and construction of the Moscow metro in confined spaces of urban development.

Gyrostatic leveling devices are integrated into the existing ADCSs (see Fig. 1) using an asynchronous physical layer interface according to the RS-485 standard and the Modbus open communication protocol. The sensors are constantly connected to a computer network; readings are taken once a minute and transmitted to the server, upon which the measurement results are compared with the evaluation criteria in real time.

Further elaboration was the development of the Russian-made AIDS "Monitron" (see Fig. 1). The system represents secure cloud software on the portal https://monitron.ru, which operates around the clock and is available through a standard Internet browser (from any operating system without having to install additional software). For all registered users, online access (through the Internet) to the

TABLE 2. Main Types of Instrumental Measurements of HS SSS Parameters

Measured parameter	Measurement method	Scale of parameter influence*	Number of observation points*	Possibility of automation
Settlement (vertical movements)	Leveling	Entire structure	+++	+
Uniform displacement	Direct and inverted plumb lines	Entire structure	+	±
Opening of joints and movement along them	Slit-metering devicea	Entire structure	++	±
Relative displacements on the base	Extensometers, strain gauges	Measuring base	+	±
Relative deformations and stresses in concrete	Strain gauges	Measuring point	++	±
Stress in reinforcement	Reinforcement force measuring devices	Structural element	++	±

* The number is conditionally indicated, from "+" to "+++," considering the potential to design an optimal number of observation points in accordance with objectives of the monitoring project.

Readings of hydrostatic leveling devices (mm)
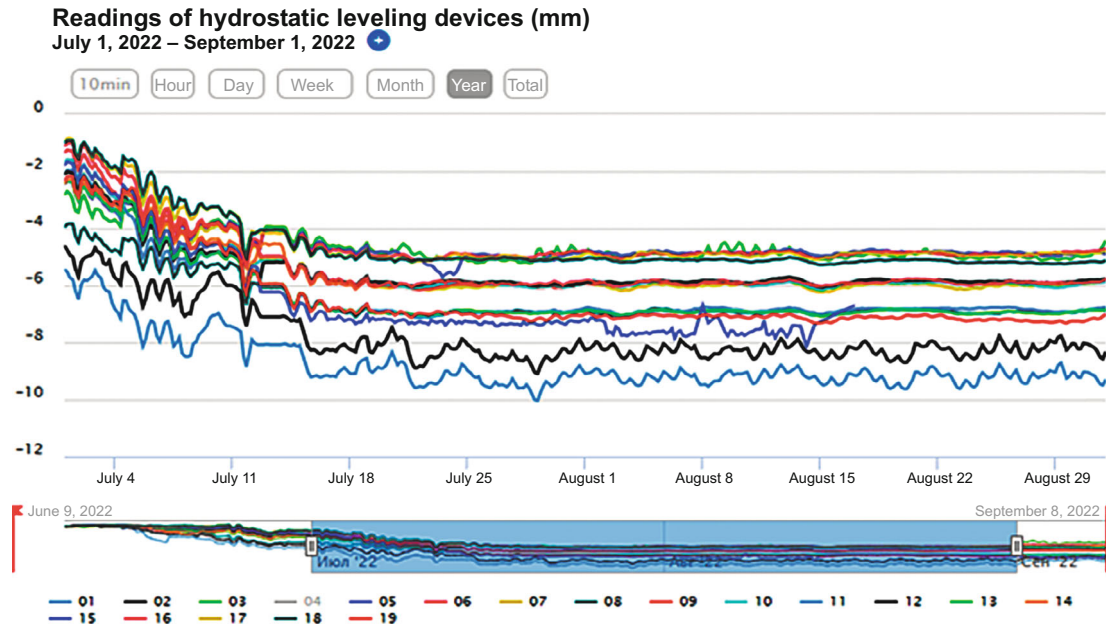July 1, 2022 – September 1, 2022

Fig. 8. Presentation of the readings of digital hydrostatic leveling devices in an interactive graphical interface through a standard browser.

results of settlement measurement is provided in real time. Figure 8 shows a flexibly customizable graphical representation of the readings of digital hydrostatic leveling devices. Powerful tools are available for prompt settlement engineering analysis and plotting. Additionally, there are services available for establishing regular reports.

The Internet browser can be run on mobile operating systems of user devices (iOS and Android smartphones), which allows for effective working with hydrostatic level device sensors in the field.

The cloud server is constantly connected to the Internet and cellular communications. Distribution of notifications regarding violation of the established evaluation criteria is conveyed through various communication channels, including public (e-mail, SMS notifications, Telegram Messenger) and corporate (corporate messengers such as Slack, Bitrix, and Pack.) channels.

If necessary, the AIDS "Monitron" can be deployed on a local server disconnected from the global Internet.

The practical knowledge of the AIDS "Monitron" includes the possibility of integrating the DT, which allows for an automated comparison of the results of settlement measurements with updated evaluation criteria according to design corridor. Additionally, the possibility of directly accessing the results of SSS calculations through the AIDS "Monitron" from an Internet browser without having to install specialized calculation programs is implemented. With a view to demonstrating the capabilities of the technology considered when implementing it on the HS, a prototype of the DT of a buttress dam was developed using the data of digital sensors of the hydrostatic leveling device "Monitron" (see Fig. 9).
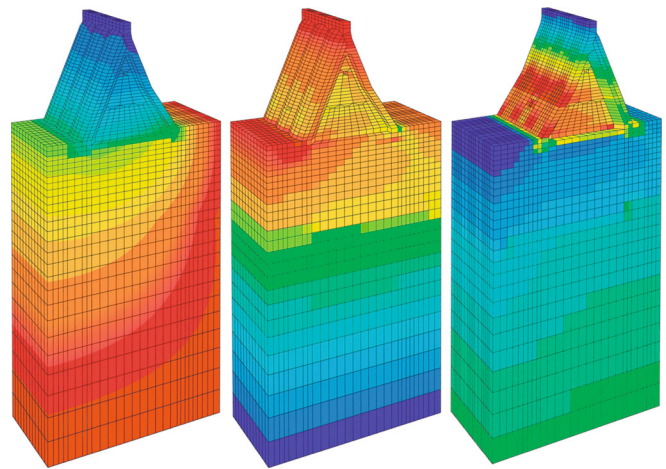

Fig. 9. Prototype of a DT of a buttress dam (isofields of the main results, enumerations from left to right): vertical displacements, horizontal stresses, and safety factor (rear view).

On account of the connection with the monitoring system, the DT was constantly validated and was in an up-to-date state consistent with the results of measurements at the points of the CME installation. Thus, the DT reproduced the SSS of the entire structure with maximum accuracy on the basis of the readings of available CME.

CONCLUSIONS

1. The main direction in the development of HS monitoring (field observations) is automation and digitalization with transition to continuous monitoring of SSS using contemporary automated telemetry CME.

2. Use of automated telemetry CME is associated with generation of a large amount of data. Therefore, it is advisable both to automate the process of assessing the HS technical condition and to intellectualize the automated assessment process using the HS SSS's DTs developed on the basis of monitoring data using modern data analysis methods (data science), particularly machine learning.

3. The DT of the HS SSS is developed via mathematical modeling using FEM in a connected formulation (with joint modeling of strength, heat transfer, and filtration). The actual characteristics of the foundation materials and soils, actual loads, impacts, and their changes over time, particularly level of the pools, change in air temperature and solar radiation over time, and filtration regime, are considered. This is necessary for reproducing a real structure, and not its idealized project, in a mathematical model in a bid to accurately predict the change in SSS as loads and impacts change during operation.

4. For development of digital twins of the HS SSS, the automated measurement of the vertical displacements of the HS characteristic points is most desired. Therefore, for the first time in the world, the technology of digital twins is integrated into an automated information and diagnostic monitoring system based on digital sensors of the hydrostatic leveling device "Monitron. "

5. All components of the "Monitron" system are of Russian origin, including the digital sensors of the hydrostatic leveling device, embedded software of the sensors, and cloud software of the information and diagnostic system. Access to the leveling results is implemented via a standard Internet browser on desktop and mobile devices for any operating system (including Russian-made ones) without the use of third-party software.

6. Within the range of the tasks of using modern automated monitoring systems along with digital twins, the achievement of a financial result associated with a reduction in insurance costs (due to risk management) and optimization of the distribution of costs for preventive maintenance overhaul is noteworthy.

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