Development and approbation of the mathematical multi-model basis of the monitoring system for the “heterogeneous filtering base – structures” systems of the responsible building objects (on the example of Zagorskaya PSPP)

D S Dmitriev\(^1\), A M Belostosky\(^{1,2,3,4,5}\), A I Nagibovich\(^{1,6}\) and K I Ostrovsky\(^1\)

\(^1\) Research & Development Centre StaDyO, office 810, 18, 3ya Ullitsa Yamskogo Polya, Moscow, 125040, Russia
\(^2\) Department of Structures, Buildings and Facilities, Russian University of Transport (RUT – MIIT), 9b9, Obrazcova Street, Moscow, 127994, Russia
\(^3\) Tomsk State University of Architecture and Building, 2, Solyanaya sq., Tomsk, 634003, Russia
\(^4\) Department of Architecture and Civil Engineering, Peoples’ Friendship University of Russia, 6, Miklukho-Maklaya str., Moscow, 117198, Russia
\(^5\) Department of Building Constructions and Computational Mechanics, Perm National Research Polytechnic University, 29, Komsomolsky prospekt, Perm, 614990, Russia
\(^6\) Russian Academy of Architecture and Construction Sciences, 24, ul. Bolshaya Dmitrovka, Moscow, 107031, Russia

stadyo@stadyo.ru

Abstract. The article reflects important aspects of interaction between three different computational complexes: ANSYS Mechanical, Midas GTS, MODFLOW, and integration of the results obtained into the software and hardware complex (PAK) for monitoring and forecasting the reliability of Zagorsk PSPP objects.

1. Introduction. Immediacy of the problem

Today, the problems of ensuring the technogenic safety of unique and responsible construction sites at all stages of the life cycle become very urgent [1]. The control (monitoring) of the technical condition of load-bearing structures and the condition of the soils at the base of the structure must be systematic and allow for the assessment of the changes taking place on the basis of correct quantitative criteria (in other words, on the basis of a comparison of the actual strength, rigidity and stability of structural elements with the relevant regulatory criteria). Modern, industry-specific systems for monitoring the technical condition of construction sites can not be based solely on instrumental monitoring (geodetic measurements, engineering-geological monitoring, measurement of loads and deformations and seismometric monitoring). Such monitoring systems should be based on adaptive finite-element calculation models, without reference to the comparison results of calculated indicators with actual data. Instrumental monitoring is of a random-pointless nature and of no practical interest.

For some, especially responsible building objects, the problem of the need to conduct several different types of calculations at once arises, which results affect each other. It is known that there is...
no universal computational software package that allows to simultaneously solve complex, non-linear tasks of geofiltration, geomechanics, strength and stability of building structures. This leads to the need to create a multi-model mathematical basis for a monitoring system combining the results from several specialized software complexes. The Research and development center StaDyO has the experience of creating the first in Russia mathematical multi-model basis of the monitoring system for the complex of structures of the Zagorsk Pumped Storage Power Plants (PSPP).

2. The monitoring object issue

Zagorsk Pumped Storage Power Plant is the largest PSPP in Russia. This hydropower object is a complex of two independent stations. The construction of the first station (PSPP-1) with capacity of 1200 MW lasted from 1987 to 2003. In 2008, the construction of the second station (PSP-2) with the capacity of 840 MW, which is located 700-800 m to the south of the first station, was started. In 2013, an accident occurred at the final stage of construction, as a result, the station building was flooded, and there was a non-projected drawdown of the building more than 1 m. Flooding occurred as a result of the occurrence of contact filtration at the base of the station building.

According to safety requirements, the station installed about 2000 sensors of control measuring equipment (CME) of various types (displacement sensors, contact strain sensors, piezometer sensors etc.). All CME sensors are combined into a semi-automated information-diagnostic system (BING-3), however, despite this, it was impossible to predict and prevent the accident.

The owner of Zagorsk PSPP - RusHydro Company made a decision to develop a hardware-software complex for monitoring the state of hydraulic structures with the possibility of predicting the impacts on the structure during long-term operation [2].

3. About hardware-software system for monitoring

The main tasks of the hardware and software complex for monitoring the state of hydraulic structures are: a comprehensive analysis of the structures and grounds current state, a risk analysis, support for decisions while assigning safety criteria. The solution of the tasks posed requires of a complex use, multicomponent approach, and therefore the structure of the hardware-software complex is rather complicated.

The hardware-software complex has three main structural blocks (the computational block, data transmission module and information-diagnostic block) (Figure 1), there is a constant exchange of data between them. The computational block included three independent computational models in three different software complexes:

1. Geofiltration model was performed in the MODFLOW software package [3]. On the basis of this model, filtration regimes for various operational cases were determined, and the mutual influence of the stations of PSPP-1 and PSPP-2. The geofiltration model was developed by the company “Vedeneev VNIIG”, JSC. Verification of the computational model was carried out by comparing the calculated data with the piezometer readings.

2. Geomechanical model, was performed in the specialized geotechnical software complex Midas GTS (verified in the Russian Academy of Architecture and Construction Sciences system). Based on the results of calculating this model, the sediments of the main structures were determined, as well as the stress-strain state of structures from the soil. The development of a geomechanical model was carried out by “Petromodelling”, LLC. Verification of the calculation model was carried out by means of comparing the calculated data with the indications of geodetic marks and other control measuring equipment.

3. Models of the Zagorsk PSPP complex, was performed in the ANSYS Mechanical software package (Figure 2). Based on the computational studies results of these finite element (FE) models, the actual and predictive stress-strain state of the complex main facilities was determined, and an analysis was made of the possible options for the restoration of the emergency station PSPP-2. The structure of the Zagorsk PSPP includes more than 100 separate structures, the main are: station buildings, floodgates and penstocks. Verification of the calculation models was carried out by comparing the
calculated data with the readings of the force transducers in the armature and the contact voltage meters. R&D Centre StaDyO was engaged in the development of the most responsible model of structures in the ANSYS Mechanical software package and the provision of data transfer between the computational models.

![Diagram](image1)

**Figure 1.** Structure of the hardware-software complex for monitoring the condition of the Zagorsk PSPP objects.

![Diagram](image2)

**Figure 2.** Model of Zagorsk Pumped Storage Power Plant.

4. **About the work of the calculation block**

An estimate of the stress-strain state of the structures of the Zagorsky PSPP was carried out in several stages (Figure 3). First, a geological model was created for the founding of the Zagorsky PSPP entire
complex. For its implementation, additional geological investigations and laboratory studies were carried out. This model formed the basis for geofiltration (1) and geomechanical (2) models.

The level of groundwater has a significant influence on the physical and mechanical properties of soils, therefore, the complex of filtration calculations in the MODFLOW program was first carried out. The results of these calculations were used as input data for the geomechanical model. The data transmission was carried out through a .txt file with the indication of the groundwater level in the predefined reference points for the two models.

At the second stage, a calculation of the geomechanical model was carried out, to which simplified models of structures were introduced. The relationship between the geomechanical model and the models of structures in the Midas GTS and ANSYS Mechanical software complexes required separate study, since the data exchange must be mutual and automated.

![Diagram of model stages](image)

**Figure 3.** The stages of assessing the stress-strain state of the structures of the Zagorsky PSPP.

There are four main options for taking into account the soil foundation in modeling the stress-strain state of structures:

1. A unified three-dimensional model of the system "soil massif - hydrotechnical structure" (in this case, the application of this approach was impossible because of the models’ large computational dimension and the incompatibility of file formats in various software complexes).

2. The superelement approach or method of substructures [4] (also did not find application in this problem because of the forming complexity of the superelement matrix in the Midas GTS).

3. Winkler base, which is an array of springs, which rigidity increases in direct proportion to the applied load [5, 6]. This approach has a number of shortcomings that prevented it from being applied in this work.

4. Specified displacement. For this type of calculation, additional kinematic boundary conditions were set in the model of the structures (ANSYS Mechanical) complex, corresponding to the movements of the soil mass obtained as a result of the geomechanical model calculation of the soil (Midas GTS). To distribute the given displacements from the nodes of the geomechanical model to the smaller grid of constructions, the interpolation and extrapolation procedure was applied (Figure 4).
5. Results of computational research

Now the hardware-software monitoring complex is in the mode of revision and debugging. Separate hardware-software complex units are developed and their integration and automation of the system as a whole are implemented.

R&D Centre StaDyO completed all the work on the creation of the monitoring system computational block. A spatial mathematical model of the stress-strain state of the hydraulic structures complex of the Zagorsk Pumped Storage Power Plant was developed with the possibility of taking into account their mutual influence. The efficiency of the multi-model calculation unit is demonstrated using scenario modeling of the PSPP-2 building non-project drawdown, as a result of an emergency event. The results of the scenario modeling showed a distribution consistent picture of the stress-strain state in the load-bearing structures of the PSPP-2 building and on the whole are consistent with the data of field surveys. The calculated pattern of crack formation on the coating of the station node is correlated with the real picture of the distribution of cracks (Figure 5).

![Figure 4](image1.png)

**Figure 4.** Transfer of base points displacements from Midas GTS to ANSYS Mechanical.

![Figure 5](image2.png)

**Figure 5.** Comparison of calculated and actual fracture patterns.

Based on the developed design model of the Zagorskaya PSPP-1 station, the study was made of the effect on the drawdown and stressed state of structures from the construction of the PSPP-2 water
drainage pit in the period from 2007 to 2008. Based on the calculations results, the drawdown of the PSPP-1 station building in the period from 2007 to 2008 exactly corresponds to the indications of geodetic marks. The change of stresses in concrete along and across the flow in the main zone of structures does not exceed 0.1 MPa. In local concentration zones in a construction number of the mounting platform, the stresses can change up to 0.55 MPa.

6. Conclusion
As a result of trial operation, a multi-model computational block of the monitoring system has confirmed its efficiency. The developed approaches to integrate results from different models allow to automate the work of the computational block.

According to the calculations results, recommendations were developed for the placement of control measuring equipment for the most effective operation of the information and diagnostic system.

The experience of creating the first multi-model framework for the monitoring system turned out to be successful. Many aspects need to be improved, but in general this approach deserves to be the best practice in the monitoring of the responsible building objects in Russia.

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