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Prediction of the movement process of the high-head dam of Sayano-Shushenskaya hydroelectric power plant during operation after the accident in 2009

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ABSTRACT.
The actuality of the study stems from the need to develop predictive mathematic models for studying the deformations of high-head dams in order to study the laws of the deformation development of the hydraulic structure and to calculate the criteria for ensuring its safety. In this regard, for the first time in the practice of studying deformations of high-head dams, this article presents the results of constructing predictive mathematical models of the dynamic type based on recurrent equations of the 1st and 2nd orders with decorrelation of input effects and transport delay. It is shown that the properties of the solution of the recurrent equation in the form of the first two conditional momentary functions of the movement process of the observed points of the deforming structure are a predictive model that allows to find predictions of specific points movement and to precompute the prediction errors. Due to the fact that seasonal changes in air temperature strongly affect the changes in the main influencing factors (hydrostatic pressure and temperature of the concrete of the dam body), the decorrelation process of the influencing factors has been realized as a result of their serial input into the model. Various combinations of input effects and discreteness of the initial data have been used, as well as a transport delay has been applied, which makes it possible to calculate the inertial delay of the dam at various loads.
The article presents the results of the construction of predictive mathematical models for describing the deformation process of the control points movement of the dam body of the Sayano-Shushenskaya hydroelectric power plant and the results of prediction by various predictive models using the inverse verification method during operation after the accident in 2009. The materials of the article are of practical value for the study of various deformation processes of high-head dams for the purpose of their safe operation.

Keywords: geodetic observations; recurrent equations; predictive model; influencing factors; decorrelation; transport delay.

1. INTRODUCTION

In accordance with the accepted "Methodology" [1] and the provisions of the Federal Law "On the Safety of Hydraulic Structures" [2], one of the mandatory conditions for diagnostic check of the dam at Sayano-Shushenskaya HPP (SSHPP) is the development of predictive mathematical models with the purpose of investigating the laws of deformation process development of the hydraulic structure and the determination of the criteria for ensuring its safety. In this case prediction is based on the results of geodetic observations of the deformations by the predictive extrapolation method and can be performed both with the help of predictive models of the kinematic type (regression) and dynamic models, depending on the completeness and quality of the available initial data [3-9].

In this context, it is possible to model various components, including those leading to irreversible changes, such as ductility, the initiation and advance of cracks, the irreversible movements of the dam body, the rheological properties of the structure base [3,9-12], etc. Models for evaluation and prediction of the strength and stability of hydraulic structures and their bases are presented in a number of works: on the basis of artificial neural networks in combination with the finite element hybrid method [13]; on the basis of the dynamic analysis of the concrete dams condition in the frequency domain due to changes in the vibrational mode [14]; by solving differential equations for deformation modeling based on data from the unified system of combined sensors [15]; as a result of using the non-stationary time series theory for the analysis of structural information using the expectation-maximization algorithm for estimation of the maximum likelihood of the probability models parameters [16]; the use of a joint approach of wavelet analysis technology to create an initial data model on the behavior of the dam, followed by the construction of an identification model capable of linking loads and dam behavior [17]; the design of an algorithm for predicting the affluent level (AL) for the purpose of an optimal filling and decrease of storage [18], etc. Note that geodetic data characterize the quantitative values of the observed points movement, and they are the result of a complex interaction of the engineering structure with its base and the external environment. The impact of various factors on the amount of movement can be assessed using the correlation and regression models [3], however, their correct application is possible only when mathematical processing can detect and take into account the duration of the inertial reaction lag of the dam to the influencing factors. Also note that models of the kinematic type primarily reflect the dependence of the deformation values on the time factor, while models of the dynamic type represent the process of investigating deformations, taking into account the joint effect of time and the main influencing factors. From this perspective, dynamic models are more perfect, they have flexible structure which can be corrected, corresponding to the physical essence of development of the deformation process to greater extent, and also realize the influence of the inertial nature of the interaction of the structure with the environment by reacting to changes in time of the main influencing factors [5].

In our earlier works [19-21], the results of testing the algorithm for constructing predictive models of the dynamic type based on recurrent equations are presented, which include: time-varying periods of the prediction foundation; discreteness of the initial data (taken as the main influencing factors) and their correlation dependence; stages of model parameters estimation, etc. For example, the discreteness of a mathematical model, i.e. the cycling of field studies should be chosen with the obligatory fulfillment of the condition that the conducted geodetic observations should cover the main laws of the deformation process development and changes in the main influencing factors. As a result of the undertaken studies, it has been found that the discreteness of field observations for 15 days has been most preferable for more correct construction of predictive models [21].

The correlation dependence of the influencing factors stems from the fact that at the majority of operated HPP seasonal changes in air temperature are functionally related to changes in hydrostatic pressure (affluent level) and the temperature of concrete in the dam body, both during the filling of the reservoir and during its "unloading" [10, 16, 22, 23]. There are also other similar links between the main influencing factors [24-27], therefore, the simultaneous insertion of the main correlating influencing factors into the constructed predictive model leads, as a rule, to its instability. Due to this fact, decorrelation of the main input effects can be realized by their serial input into the model, for example, as shown in the authors' work for a decorrelation model of the 1st order [19]. Such method makes it possible to take into account the residual part of the inertial delay correctly and to predict according to the actual values of the input influencing factors observed in advance during the transport delay interval.

2. MATERIALS AND METHODS

In accordance with the recommendations [1], radial movements of the dam crests, i.e. the left-bank section 18, the main section 33 and the right-bank section 45 and the corresponding values of the parameters of the affluent level and the temperature of the concrete at the base points T_{low}, T_{top} have been selected as one of the control diagnostic indicators of the Sayano-Shushenskaya HPP [3].

As initial data and inverse verification of the constructed mathematical models, the measurement data obtained from [3,6,10,12,24] were used. The prediction period for all constructed models was as follows: from April 30, 2007 to May 15, 2008 (Fig. 1). This choice was justified by the fact that this time interval was included in the period when the dam remained monolithic after repair (1995-2003), while taking the design head [6], as well as by the fact that this time period preceded the accident on September 19, 2009. Several variants of predictive mathematical models of dynamic type based on recurrent equations of the 1st and 2nd orders have been constructed to study the movements of the controlled points of the SSHHP dam. The choice of recurrent equations of the 1st and 2nd orders for prediction stems from the fact that this type of equations allows to calculate the predictive values of the controlled points obviously and stepwise, starting from the last values of movements and residual errors during the prediction foundation period. At the same time, this type of equations correctly takes into account the inertial nature of the interaction of the structure with the environment, responding to the main influencing factors.

As the main input effects, the following has been taken: U_k - the value of the affluent level (hydrostatic pressure) and $T_{k.low}; T_{k.top}$ - the temperature of the concrete of the dam body at the lower and upper base points. The sequence of input has been determined by the primary and secondary effects of the factors, i.e. initially, the effect of temperature $T_{k.low}$ or $T_{k.top}$ has been inserted at the base points, and then the hydrostatic pressure, or their combinations have been input.

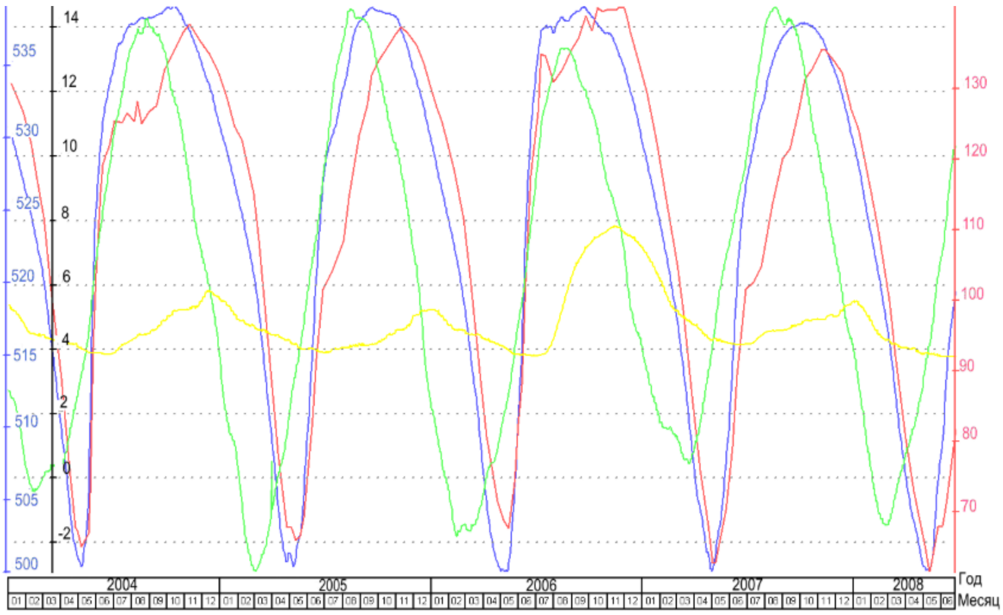

Fig. 1 Diagrams of the dam crest movements, changes in the AL and temperature of the concrete of the dam body at the base point T_{low} and T_{top} in time along the section 33: -- radial movements; -- head water; -- temperature of concrete T_{low}; -- temperature of concrete T_{top}.

As the initial recurrent equations of the 1st and 2nd orders, the following models have been used [5,19]:

$$U_k = \varphi_1 U_{k-1} + \beta_1 T_{k.low} + U_0;$$
$$x_k = \varphi_2 x_{k-1} + \beta_2 T_{k.low} + x_0;$$
$$\Delta x_k = \varphi_3 \Delta x_{k-1} + \beta_3 \Delta U_k;$$
$$\omega_k = AP2.$$

(1)

and

$$U_k = \varphi_1 U_{k-1} + \beta_1 T_{k.low} + \beta_2 T_{k.top} + U_0,$$
$$x_k = \varphi_2 x_{k-1} + \varphi_3 x_{k-2} + \beta_3 T_{k.low} + x_0,$$
$$\Delta x_k = \varphi_4 \Delta x_{k-1} + \beta_4 \Delta U_k + \Delta x_0,$$
$$\omega_k = AP2.$$

(2)

In the models (1) and (2), the first two equations represent the main input effects $U_k; T_{k.low}$ and $T_{k.top}$ causing the movement x_k and express the dependence of the hydrostatic pressure and movement on the concrete temperature of the dam body. The third equation describes the dependence Δx_k on ΔU_k, where Δx_k is the differences between the actual values of movements x_k found by the second equation and the prediction calculated on the basis of the prediction period, and ΔU_k is similar corresponding differences between the actual values U_k calculated by the first equation; the fourth equation is one of the varieties of the noise component, for example, *AP*2, the solution of which will be shown below.

Replacement of the values of x_k, U_k, $T_{k.low}$ and $T_{k.top}$, and their time-centered values $\dot{x} = x_k - \bar{x}$, $\dot{U} = U_k - \bar{U}$, $\dot{T} = T_{k.low} - \bar{T}$ ($\bar{x}, \bar{U}, \bar{T}$ - average values of movement and input parameters: the affluent level and temperature taken during the prediction foundation period) in expressions (1) and (2), as shown earlier in the work [20], makes it possible to simplify the computation process substantially, and increases the conditioning of systems of normal equations.

The solution of the systems of equations (1) and (2) has been implemented in stages. At the first stage, the dependence of the change in the hydrostatic pressure on the air temperature has been determined (however, note that for the construction of the predictive models we have been used the temperature both in the lower $T_{k.low}$ and in the upper base point $T_{k.top}$).

Using the method of least squares (MLS), based on the results of observations of input $\{T_{k.low}\}$ and output $\{U_k\}$, the model parameters have been initially estimated during the prediction foundation period k = 1,2, ..., N. For this purpose, the functional $F_1(\varphi_1, \beta_1) = \sum_{k=2}^{N} \left(U_k - \hat{U}_{k/k-1}\right)^2$ has been minimized; through $\hat{U}_{k/k-1}$ the conditional mathematical expectation of the first equation from the expressions (1) and (2) has been denoted, which has the following form for the model (1):

$$M\left\{U_k / U_{k-1}, T_{k.low}\right\} = \hat{U}_{k/k-1} = \hat{\varphi}_1 U_{k-1} + \hat{\beta}_1 T_{k.low} .$$

(3)

The parameter estimators $\hat{\varphi}_1, \hat{\beta}_1$ have been obtained in the process of solving the corresponding systems of normal equations. For the constructed models of the 1st and 2nd order, all possible first equations (4) have been obtained expressing the dependence of the hydrostatic pressure on the temperature of the dam body concrete:

$$U_k = 0,7180U_{k-1} + 0,7754T_{k.low} + 142,243;$$
$$\hat{U}_{k/k-1} = 0,8612U_{k-1} + 0,6062T_{k.low} - 0,0748T_{k.top} + 68,848; \qquad (4)$$
$$U_k = 0,7764U_{k-1} + 3,0060T_{k.top} + 100,260.$$

At the second stage, the dependence of the movement on the temperature effect has been determined, i.e. the parameters have been evaluated based on the results of observations of the input $\left\{T_{k.low}\right\}$ or $\left\{T_{k.top}\right\}$ and output $\left\{x_k\right\}$ similar to the estimation at the first stage. For this purpose, the functional $F_2\left(\varphi_2, \beta_2\right) = \sum_{k=2}^{N}\left(x_k - \hat{x}_{k/k-1}\right)^2$ has been minimized; $\hat{x}_{k/k-1}$ is conditional mathematical expectation of the second equation from the expressions (1) and (2), which, for example, which has the following form for the model (1):

$$M\left\{x_k / x_{k-1}, T_{k.low}\right\} = \hat{x}_{k/k-1} = \hat{\varphi}_2 x_{k-1} + \hat{\beta}_2 T_{k.low} . \qquad (5)$$

The parameter estimators $\hat{\varphi}_2, \hat{\beta}_2$ have been obtained in the process of solving the systems of normal equations for the corresponding models. For all constructed models, all possible second equations (6) have been obtained for the models (1) and (2) expressing the dependence of the movement on the temperature of the dam body concrete:

$$x_k = 0,8174x_{k-1} + 1,1214T_{k.low} + 11,523;$$
$$\hat{x}_{k/k-1} = 0,6555x_{k-1} + 1,0275T_{k.low} + 13,2756T_{k.top} - 31,219;$$
$$\hat{x}_{k/k-1} = 0,2950x_{k-1} + 0,4362x_{k-2} + 1,6151T_{k.low} + 13,027; \qquad (6)$$
$$x_k = 0,5322x_{k-1} + 20,7204T_{k.top} - 45,273.$$

At the third stage, the corresponding differences Δx_k have been determined between the actual values and values of the movements x_k, calculated using the second equation, and the difference ΔU_k between the actual values and values of hydrostatic pressure U_k calculated using the first equation.

Further, the parameters have been estimated based on the results of observations of the input $\left\{\Delta U_k\right\}$ and output $\left\{\Delta x_k\right\}$ as a result of minimization of the functional

$F_3(\varphi_3,\beta_3)=\sum_{k=2}^{N}\left(\Delta x_k-\Delta\hat{x}_{k/k-1}\right)^2$; where through $\hat{x}_{k/k-1}$ the conditional mathematical expectation of the third equation from the expressions (1) and (2) has been denoted, which has the following form for the model (1):

$$M\left\{\Delta x_k/\Delta x_{k-1},\Delta U_k\right\}=\Delta\hat{x}_{k/k-1}=\hat{\varphi}_3\Delta x_{k-1}+\hat{\beta}_3\Delta U_k\ . \tag{7}$$

The parameter estimators $\hat{\varphi}_3,\hat{\beta}_3$ have been obtained in the process of solving the systems of normal equations for the corresponding models. For all constructed models, all possible third equations (8) have been obtained, expressing the differences between the actual values x_k and values ΔU_k calculated using the second equation and the corresponding differences U_k between the actual values and values calculated using the first equation:

$$\begin{aligned}
\Delta x_k &= 0,0062\Delta x_{k-1}+1,6224\Delta U_k+0,1338+1,2290\omega_k;\\
\Delta x_k &= 0,3803\Delta x_{k-1}+1,0213\Delta U_k+4,205+1,8630\omega_k;\\
\Delta x_k &= 0,0355\Delta x_{k-1}+1,5566\Delta u_k-0,128+1,2592\omega_k;\\
\Delta x_k &= 0,3808\Delta x_{k-1}+1,0372\Delta u_k-2,957+1,9418\omega_k.
\end{aligned}$$

(8)

At the last stage, the order of the autoregression model and the estimation of the correlation function parameters [28] have been determined using the formula for estimating time series:

$$\hat{K}_\varepsilon[m]=\frac{1}{N}\sum_{k=1}^{N-m}\varepsilon_k\varepsilon_{k+m}, \tag{9}$$

where time shift is m =0, 1, 2… $M \lhd N$.

Residual errors, as a result of all remaining unaccounted and random factors effect $\varepsilon_k=x_k-\hat{x}_{k/k-1}=\gamma\omega_{k-1}$, allow us to characterize the predictive model under construction in the context of its structural identification; at the same time, it is a characteristic of the properties of the noise component ω_k. As a result, investigating the influence of residual errors analytically, there is the possibility of mathematical description of the noise process ω_k by certain models of autoregression of the 1st or 2nd order [28].

The choice of the order of the autoregression model has been implemented in the process of analyzing the plotted diagrams of the correlation function according to residual errors. For of all the constructed models, the plotted diagrams have a form that is very close to that shown in Figure 2. This indicates that the description of the noise process should be produced by the following autoregressive model of the 2nd order:

$$\omega_k=\mu\omega_{k-1}+\eta\omega_{k-2}+\xi_k, \tag{10}$$

where μ,η – estimated parameters.

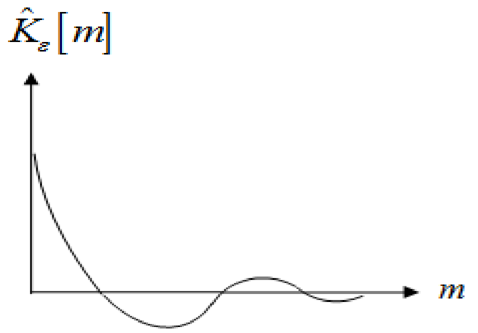

Fig.2 Correlation function diagram

The estimation of parameters μ,η has been implemented as a result of minimization of the following functional: $F_4(\mu,\eta)=\sum_{m=1}^{M}\left(\hat{K}_{\varepsilon}[m]-\mu\hat{K}_{\varepsilon}[m-1]-\eta\hat{K}_{\varepsilon}[m-2]\right)^2$, i.e. the estimates μ,η have been in the process of solving the corresponding system of normal equations, and the coefficient γ has been estimated using the formula:

$$\hat{\gamma}=\sqrt{\frac{\hat{K}_{\varepsilon}[0]}{\hat{K}_{\omega}[0]}}. \tag{11}$$

To estimate the parameters $AP2$, systems of normal equations for all the corresponding models have been obtained, for which all the estimates $\hat{\mu};\hat{\eta};\hat{\gamma}.$ have been calculated: The constructed models of the noise component ω_k are the following:

$$\begin{aligned}
\omega_k &= 0,3790\omega_{k-1}+0,1530\omega_{k-2}+\xi_k;\\
\omega_k &= 0,4404\omega_{k-1}-0,1255\omega_{k-2}+\xi_k;\\
\omega_k &= 0,4418\omega_{k-1}+0,1490\omega_{k-2}+\xi_k;\\
\omega_k &= 0,5736\omega_{k-1}-0,2255\omega_{k-2}+\xi_k.
\end{aligned} \tag{12}$$

3. RESULTS

The finally constructed predictive models are accordingly the following:

Model $\Delta x(\Delta U_k;T_{k.low};x_0;U_0)$

$$\begin{aligned}
U_k &= 0,7180U_{k-1}+0,7754T_{k.low}+142,243;\\
x_k &= 0,8174x_{k-1}+1,1214T_{k.low}+11,523;\\
\Delta x_k &= 0,0062\Delta x_{k-1}+1,6224\Delta U_k+0,1338+1,2290\omega_k;\\
\omega_k &= 0,3790\omega_{k-1}+0,1530\omega_{k-2}+\xi_k.
\end{aligned} \tag{13}$$

Model

$\Delta x(\Delta U_k;T_{k.low};T_{k.top};x_0;U_0)$

$$\hat{U}_{k/k-1} = 0{,}8612U_{k-1} + 0{,}6062T_{k.low} - 0{,}0748T_{k.top} + 68{,}848;$$
$$\hat{x}_{k/k-1} = 0{,}6555x_{k-1} + 1{,}0275T_{k.low} + 13{,}2756T_{k.top} - 31{,}219;$$
$$\Delta x_k = 0{,}3803\Delta x_{k-1} + 1{,}0213\Delta U_k + 4{,}205 + 1{,}8630\omega_k; \quad (14)$$
$$\omega_k = 0{,}4404\omega_{k-1} - 0{,}1255\omega_{k-2} + \xi_k.$$

Model $\Delta x(\Delta U_k; T_{k.low}; x_0; U_0)$

$$U_k = 0{,}7180U_{k-1} + 0{,}7754T_{k.low} + 142{,}243;$$
$$\hat{x}_{k/k-1} = 0{,}2950x_{k-1} + 0{,}4362x_{k-2} + 1{,}6151T_{k.low} + 13{,}027;$$
$$\Delta x_k = 0{,}0355\Delta x_{k-1} + 1{,}5566\Delta U_k - 0{,}128 + 1{,}2592\omega_k; \quad (15)$$
$$\omega_k = 0{,}4418\omega_{k-1} + 0{,}1490\omega_{k-2} + \xi_k.$$

Model $\Delta x(\Delta U_k; T_{k.top}; x_0; U_0)$

$$U_k = 0{,}7764U_{k-1} + 3{,}0060T_{k.top} + 100{,}260;$$
$$x_k = 0{,}5322x_{k-1} + 20{,}7204T_{k.top} - 45{,}273;$$
$$\Delta x_k = 0{,}3808\Delta x_{k-1} + 1{,}0372\Delta U_k - 2{,}957 + 1{,}9418\omega_k; \quad (16)$$
$$\omega_k = 0{,}5736\omega_{k-1} - 0{,}2255\omega_{k-2} + \xi_k.$$

The final stage of the predictive model development consisted in analyzing the results obtained with control prediction based on the principle of inverse verification. In case of unsatisfactory quality of the constructed predictive model, all the previous stages of its development have been repeated again in order to find a different type or structure of the model, or to consider the choice of the main influencing factors and the possible transport delay more carefully, and the choice of the prediction foundation period that most adequately describe the deformation process.

4. DISCUSSION

Note the following special features. Each cycle of the dam operation has two branches: a loading branch (reservoir filling) and an unloading branch (reservoir decrease). In this case, the movements of the controlled base point in both branches of the cycle occur along different curvilinear trajectories during the entire operation cycle of the dam, depending on the factors influencing it. It seems reasonable to distinguish the "nominal" and "non-nominal" behavior of the dam, for example, such as: excessive inflow for the period of operation of 2006-2007; operation period 2009-2010 - accident and abnormally cold winter in 2009; 2010-2011 – transfer of the beginning of the reservoir filling to the end of May for the purpose of additional preheating of the downstream face. Such situations lead to an additional impact on the movement of the dam and temperature changes $T_{k.low}$ and $T_{k.top}$, and the same predictive model, for example, describing the loading branch quite well, turns out to be useless for describing the unloading branch and vice versa. Note that when cooling concrete at the lower base point for 1°, the deflection of the dam crest of the section 33 is increased by 2.4 mm, and when cooling the concrete at the upper base point $T_{k.top}$ for 1°, the deflection of the dam crest is reduced by 2.2 mm [3]. For example, the analysis of the initial data has shown [3] that the reason for the higher growth of the values of the maximum radial movements has been a noticeable change in the temperature of the concrete of the dam body near the upstream face, that is clearly visible on the diagram (Figure 1), while the difference in temperature variations $T_{k.top}$ at "nominal" and "non-nominal" behavior of the dam is up to $2,5-3^{\circ}$. At the same time, the abnormally cold winter of 2009-2010 led to greater deflection of the dam section than in case of "nominal" behavior due to additional cooling of the downstream face $T_{k.low}$. It seems that for correct prediction and correct reflection of various situations of the dam behavior, it is necessary to introduce the effects of temperature variations $T_{k.low}$ and $T_{k.top}$ in the constructed models gradually.

5. CONCLUSIONS

Analysis of the diagrams of temperature $T_{k.low}$ and AL changes has shown their difference in delay from the movement amount in 2009-2010 in comparison with closely related delay diagrams during the periods of operation in 2007-2008 (the prediction foundation period on which the model has been constructed) and 2008-2009. And this difference appears around the end of January and continues until the end of the reservoir operation. In these months there has been gross difference in the predictive values of the decrease branch in 2009-2010. A similar delay has been observed along the loading branch in 2008-2009 in comparison with the loading branch in 2007-2008. It appears from the end of June and continues until the end of October. Therefore, the use of such method as the introduction of transport delay in prediction has a positive effect on the correction of predictive values. In addition, it is necessary to note one more fact, namely, that the dam return to the initial condition (during the reservoir decrease) differs from the predictive values by about 7-8 mm. This deviation is still inexplicable to us, but this fact requires additional study as for the last 3 years of the dam operation in 2009-2010, 2010-2011 and 2011-2012 this value has changed to 69,13 mm, 70,36 mm and 72 mm respectively.

Table 1 presents the results of prediction by the model (14) with the help of inverse verification (the final error has occurred after the introduction of transport delay).

Table 1. The results of prediction by the model (14) with the help of inverse verification

Model discreetness	Stage of 2008-2009			Stage of 2009-2010			Stage of 2010-2011		
	Prediction results, mm			Prediction results, mm			Prediction results, mm		
	Prediction date	Prediction error	Final error	Prediction date	Prediction error	Final error	Prediction date	Prediction error	Final error
1	2	3	4	5	6	7	8	9	10
15.05.08				5.05.09	+0.8	+0.8	13.05.10	+7.2	+6.7
30.05.08	30.05.08	-3.8	+1.6	30.05.09	-0.1	-0.1	23.05.10	+1.9	
15.06.08				03.06.09	-0.4	-0.4	10.06.10	+3.4	+1.6
30.06.08	30.06.08	-9.4	-2.3				30.06.10	+6.1	+2.8
15.07.08				1.07.09	-1.4	-1.4	09.07.10	+9.2	+3.3
30.07.08				27.07.09	+3.8	+3.8			
15.08.08				**17.08.09 - accident**					
30.08.08				27.08.09	+3.5	+3.5	30.08.10	+1.3	+1.3
15.09.08	11.09.08	-9.1	+1.5				9.09.10	+3.1	+3.1
30.09.08				25.09.09	+1.9	+1.9			
15.10.08	07.10.08	-4.2	+3.2				14.10.10	+0.8	+0.8
30.10.08				29.10.09	-1.2	-1.2	28.10.10	+4.6	+3.1
15.11.08	13.11.08	-1.6	-1.6	13.11.09	-1.7	-1.7			
30.11.08	26.11.08	-0.5	-0.5						
15.12.08				11.12.09	-0.7	-0.7	14.12.10	+7.7	+1.9
30.12.08	27.12.08	+1.9	+1.9						

15.01.09	11.01.09	+1.2	+1.2	12.01.10	+0,9	+0,9	11.01.11	-1.8	-1.8
30.01.09									
15.02.09	13.02.09	+0.1	+0.1	11.02.10	+4.3	+2.1	11.02.11	-0.15	-0.15
28.02.09				25.02.10	+6.2	+1.3			
15.03.09	13.03.09	-0.4	-0.4	11.03.10	+4.5	+1.4	11.03.11	+2.8	+2.8
30.03.09				30.03.10	+3.3	-3.1			
15.04.09							13.04.11	+2.4	+2.4
30.04.09	28.04.09	-1.7	-1.7	28.04.10	+1.5	+2.0			
15.05.09	5.05.09	+0.8	+0.8	13.05.10	+7.2	+6.7	12.05.11	+8.3	+8.3

Note one more specific feature of parameters estimation by the method of least squares when constructing a predictive model. The sequence of performing the estimation stages is determined by the nature of the predicted task. If the model is designed to predict the average value from a set of realizations of the process or an individual realization, then in the first stage it is advisable to estimate $\hat{\varphi}, \hat{\beta}$ by mathematical expectation, and at the second stage it is necessary to estimate the noise properties from the residual variance. If it is necessary to obtain more accurate prediction of individual observable realizations of the process, this can be achieved by approximation at the first stage of the correlation function and minimization of the functional for estimate $\hat{\varphi}$. Then, using the estimate $\hat{\varphi}$ for approximation of the mathematical expectation and variance, we can estimate $\hat{\beta}$ and the noise properties by minimization of the corresponding functionals. We can assume that prediction combines different aspects of geodetic research performed with a certain accuracy and that can be considered as the results of observations ahead of time, and the mathematical models constructed for prediction can be used to analyze the mechanism of processes occurring in structures on the basis of generalized laws of the observed points movements development.

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