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The prediction of the displacements of the body of the Solina Dam as a tool to improve safety of the facility

Aleksandra Bąk

AGH University of Science and Technology, 30 Aleja Mickiewicza Str., 30-059 Cracow, Poland

E-mail address: abak@agh.edu.pl

ABSTRACT

Social and economic development of the country to a large extent is determined by the energy sector. Structure of electricity production in Poland shows a significant share of fossil fuels. According to the Energy Market Information Centre coal is particularly important to ensure sufficient energy supply in Poland. Its participation in the national production comprises nearly 50%. Another important energy source is lignite, which accounts for more than 34% of electricity production. Unfortunately, the energy system based mainly on limited fuel resources requires the search for new energy sources. This situation makes the use of water energy an interesting solution. Low hydropower potential in Poland, as well as economic and formal – legal aspects causes that mentioned potential is used only in 12%, which is 1,5% of national electricity production. Both the low utilization of energy water potential of the country, as well as the benefits from the development of hydropower indicate the need to take actions aimed at hydropower development, one of them are focused on modernization and renovation of existing facilities. Because of the lowland character of the country, the pumped – storage power plants are the most important in electricity production. To ensure their stable share in national energy sector it is important to control current state of both power plants and its associated facilities, such as dam. To this aim, there were created many statistical methods focused on displacements of the dam during the normal operation of the object. Previous analysis allowed for the conclusion, that the EDF model reflects measurement data obtained from the body of the dam, the most faithfully. This assumption allowed for forecasting of future displacements of mentioned measurement points. The main assumption of presented modeling was to create simple tool to support the monitoring of the object and ensure its safety operation.

***Keywords*:** the Solina Dam; Hydroelectric Power Plant in Solina; displacements; modeling, forecasting; safety of the facility

1. INTRODUCTION

Dams, as multifunctional facilities are created to support inter alia tourism, recreation or flood protection. They also play a vital role in supporting the energy sector. In such situation is also the Solina Dam. Its safety determines the stable share of Hydroelectric Power Plant in Solina in the national electricity production. This is particularly important because stability of energy sector condition the social and economic development of the country. Additionally, measures to support the national energy sector are especially important by the reason of growing energy demand. Unfortunately, structure of electricity production in Poland shows a significant share of fossil fuels. According to the Energy Market Information Centre coal is particularly important to ensure sufficient energy supply in Poland. Its participation in the national production comprises nearly 50%. Another important energy source is lignite, which accounts for more than 34% of electricity production. The energy system, that is based mainly on limited resources of fossil fuels show the great importance of renewable energy sources. This situation makes the use of water energy an interesting solution.

Currently, the share of hydropower in the world's electricity production reaches 16%. Significant share in energy production have run – of - river power plants, that work constitutes 8% of energy produced from renewable sources. The greatest hydroelectric potential, and thus the largest production is observed in China, Brazil, Canada, USA and Russia. In Europe, the potential of hydropower plants is used in 47%. Unfortunately, the situation in Poland is slightly different – a low hydropower potential is dictated by the lowland character of the country. In addition, small precipitation contributes to the fact, that the energy of water resources is estimated at 13,7 GWh/year [1]. Moreover, economic and formal – legal aspects causes that mentioned potential is used only in 12%. That corresponds to the production of 1,5% of national electricity production [2].

Development plans for the energy sector, as well as commitments on climate protection and the limited resources of fossil fuels show benefits from the development of hydropower. However, such measures require the development of hydrotechnical infrastructure. This type of actions meets with social disapproval, because of the threat posed by the exploitation of large hydraulic structures, as dams. Mentioned social disapproval is also the result of common conviction about harmful effect of the barrages and dams to the environment. The construction of the dams is associated with difficulties in fishing migration, the solution in this case are the fish passes. A major problem pointed by environmentalists is also limitation of the river sediment transport, reducing the possibility of self – purification of the river and thus the deterioration of water quality. A significant problem, not only because of the environment, but also safety of the facility, is a bottom erosion below the barrage. This phenomenon seriously threatens hydrotechnical facilities. Mentioned aspects constitutes a restriction for the new hydrotechnical infrastructure. Therefore, actions focused on modernization and expansion of existing facilities are an interesting solution. The stable share of hydropower in the national energy sector is possible inter alia by ensuring safe operation of power plants and its accompanying hydraulic facilities, as dams. In presented analysis the mentioned problem was undertaken. The measures to support the monitoring and control of the Solina Dam indirectly provides a stable share of Hydroelectric Power Plant in Solina in national energy production.

2. MATERIALS AND METHODS

2. 1. The Solina Dam and Hydroelectric Power Plant in Solina

The subject of the analysis is the Solina Dam and its accompanying Power Plant in Solina. The Dam, created on the 325,4 km of the River San, allowed to create an artificial reservoir, that is the upper reservoir to the Power Plant. The object was established on the San River, it is 82 m height and a length of 664 m. Impressive cubic of concrete massive (760,000 m^3) of the Dam made it the largest volume of concrete massive. The construction of this facility has allowed to create the largest artificial lake in Poland - Lake Solina. The capacity of this reservoir is 497 million m^3 at the water surface of 2,200 ha. Pipes placed in the dam leads the water to the power station's turbines.

Solina Hydroelectric Power Plant was launched in 1968. It is a pumped – storage power plant, equipped with four Francis type turbine sets. Two of these turbo sets operates in the production of energy, while the other two during the day are producing energy, and in the night they are pumping water from Lake Myczkowieckiego to Solina Lake. Originally installed capacity of Power Plant amounted to 136 MW, after the modernization completed in 2003 the capacity of the Power Plant reached 200 MW. Annual production of electricity in Solina is 230 GWh. Both the Power Plant, and the Dam are important for the national economy, it is in fact a crucial facility of surface water management in south – eastern Poland. One of the main reasons why the Power Plant was established was the use of the energy potential of the upper part of the river San. Furthermore, created reservoir perform important flood protection function. It also serves to the recreational purposes. The obvious function of the reservoir is also raising the minimum flows. However, both the size of created Dam and the Lake makes their exploitation involves a high flood risk, hence the importance of monitoring this type of facilities. For this purpose, many methods of modeling and interpretation of the displacements observed on different parts of the dams were created.

2. 2. The EDF model

Many graphical and statistical methods to support the interpretation of mentioned measurement data were established [3]. This analysis, like the previous research is based on one of the first statistical models. The used model was created to support the interpretation of the vertical displacements observed using pendulums located on arch dams. This model is a mathematical description of the changes observed on the surface of the object during normal operation of the dam. The EDF formula (1) illustrates the reaction of the facility to the influence of the impact of seasonality, rheological and hydrological factors.

$$M(z,t) = T(t) + S(t) + H(z) \quad (1)$$

where:
M (z, t) – the value of the displacement;
T (t) – the rheological influence;
S (t) – the seasonal effect;
H (z) – the influence of hydrological effect.

The impact of rheological factor (2), as well as the impact of seasonality (3) are expressed as a function of time. While the influence of hydrological factor (4) on the structure is presented using the function of the upper water level [4].

$$T(t) = A + B \cdot e^{-Ct} \tag{2}$$

$$S(t) = D \cdot \sin(\frac{2\pi t}{365} + E) + F \cdot \sin\left(\frac{4\pi t}{365} + G\right) \tag{3}$$

$$H(z) = Hz + Iz^2 \tag{4}$$

where:
A, B, C, D, E, F, G, H, I – the coefficients characteristic to each measurement point;
t – the time;
z – the upper water level.

The EDF model, as one of the first statistical models, has a number of modifications. Despite the large number of methods, the EDF model best fits for the assumptions of analysis. Both, analyzed data sequences and environmental data were implemented to MATLAB. Then, based on the implemented model, the coefficients characteristic for each measurement point were generated. Previous analysis [5] has confirmed the usefulness of the presented method as a tool to interpret the measurement data obtained from measurement points located on the body of the Solina Dam. Therefore, further steps towards forecasting vertical displacements were undertaken.

3. ANALYSIS

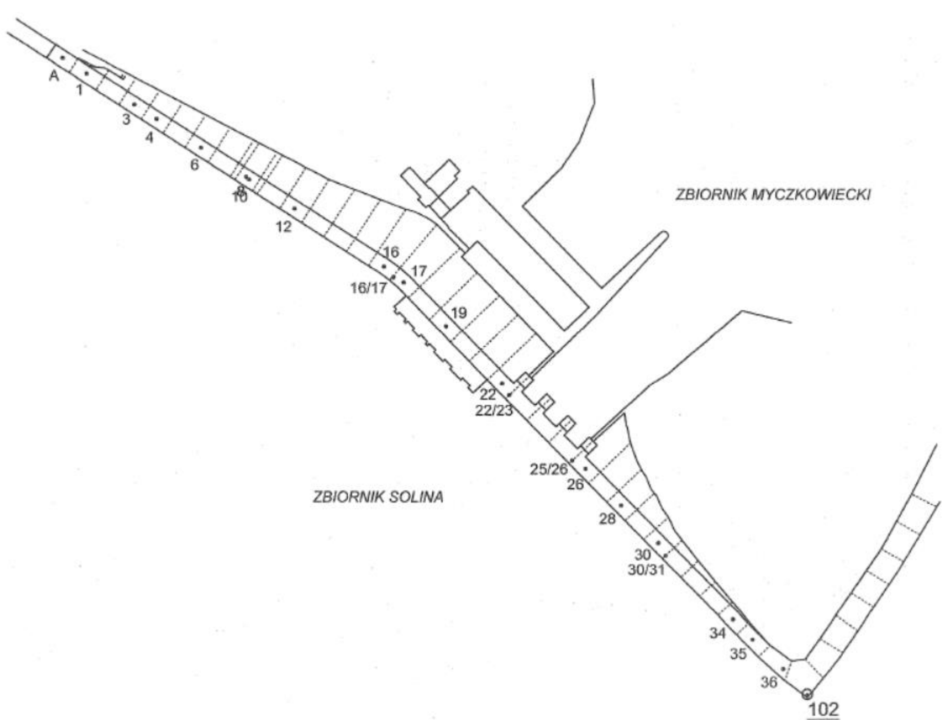

Figure 1. Location of measurement points on the body of the Solina Dam
Source: IMGW [6].

In this analysis measurement data of the vertical displacements obtained from the measurement points located on the body of the Solina Dam (Figure 1) were forecasted. Previously conducted researches confirmed that measurement data obtained from mentioned points were able to modeled using the EDF model. These conclusions allowed for further analysis of forecasting the displacements in next measurement step. Predictions were generated based on four different periods - 10, 12, 15 and 18 years of operation of the dam. Using chosen model and mentioned data sequences the coefficients characteristic for each measurement point were generated. The coefficients appropriate for the different forecasting periods allowed to predict the displacement for the next measuring period, which in the case of measurement points located on the body of the dam is half of the year.

Analysis based on 10 years of exploitation of the Solina Dam.

For nearly 60% of the measurement data it was impossible to reliably match the EDF model. The reason for this situation is the measurement frequency and the length of the data sequence. Satisfactory fit and forecasts of displacement in next measurement step were achieved only in 13% of analyzed measurement points, for example to the point no. 39-1d (Figure 2) and 40-2d (Figure 3).

Analysis based on 12 years of exploitation of the Solina Dam.

Extending the data sequences for two years led to a slight improvement of fit of measurement data. It was still impossible to match the model to measurement data obtained from 45% of analyzed points. However, the number of points very well matched using the EDF model has increased. These points are, inter alia points no. 26-2d (Figure 4) and 39-1d (Figure 5). In both cases, the forecasts for the next measurement step were overestimated by more than 2 mm.

Analysis based on 15 years of exploitation of the Solina Dam.

Data sequence corresponding to 15 years of exploitation of the facility significantly improved both possibilities of modeling and forecasting. Nevertheless, measurement data from 35% of analyzed points still made it impossible to model using the EDF model. In many cases, for example points no. 20-1d (Figure 6) and 26-1d (Figure 8), there were achieved visible improvement of modeling.

Analysis based on 18 years of exploitation of the dam.

The longest forecasting period allowed for significant improvement of modeling measurement data. However, data sequences of more than 15% of measurement points did not allow for reliable match with the EDF model. A slight improvement was achieved for more than 17 % of analyzed points. While significant progression was obtained for more than 52 % of measurement points, including point no. 31-1d (Figure 8) and 38-2d (Figure 9). The forecast was also improved, the modeled values differed from actual values of displacements of slightly more than 1 mm. Difficulties associated with the modeling and forecasting of the displacements observed on the body of the Solina Dam are the result of measurement frequency. Presented analysis allowed for the conclusion that the forecasting of the points measured with frequency of 2 readings per year requires the data sequences corresponding at least to 15 years of exploitation of the facility.

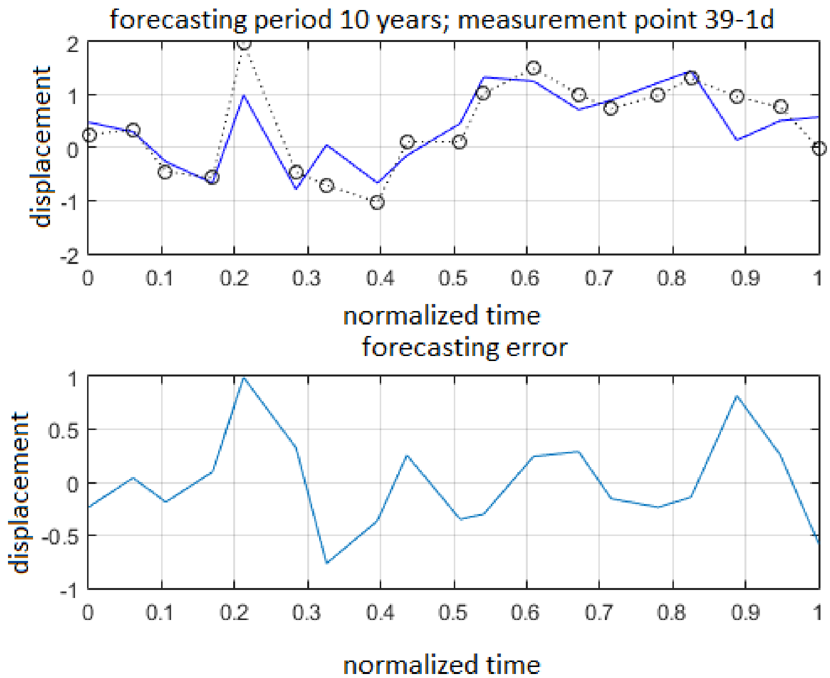

Figure 2. Approximation and approximation error, the body of the Solina Dam, measurement point no. 39-1d, forecasting period: 10 years.
Source: Own work.

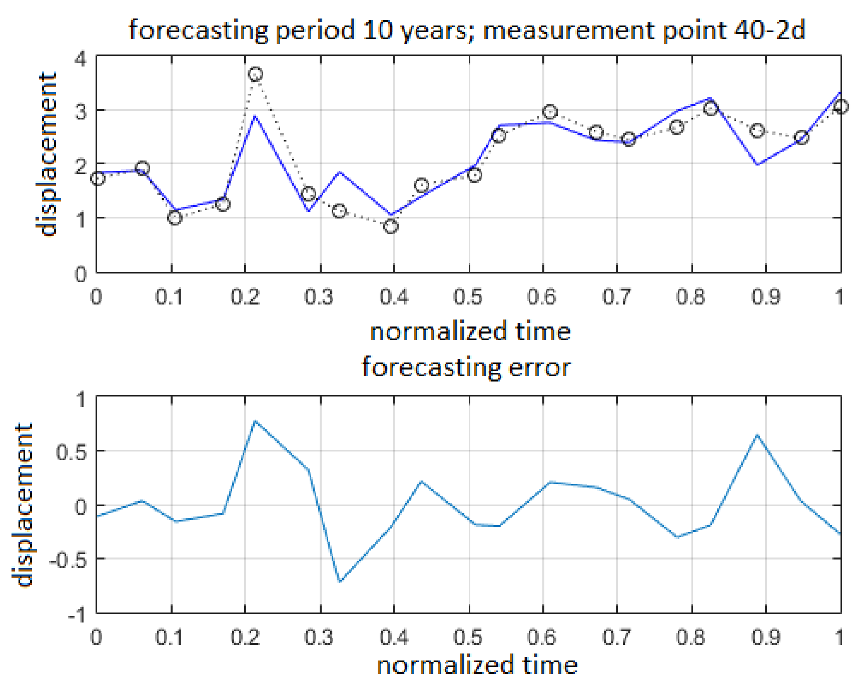

Figure 3. Approximation and approximation error, the body of the Solina Dam, measurement point no. 40-2d, forecasting period: 10 years.
Source: Own work.

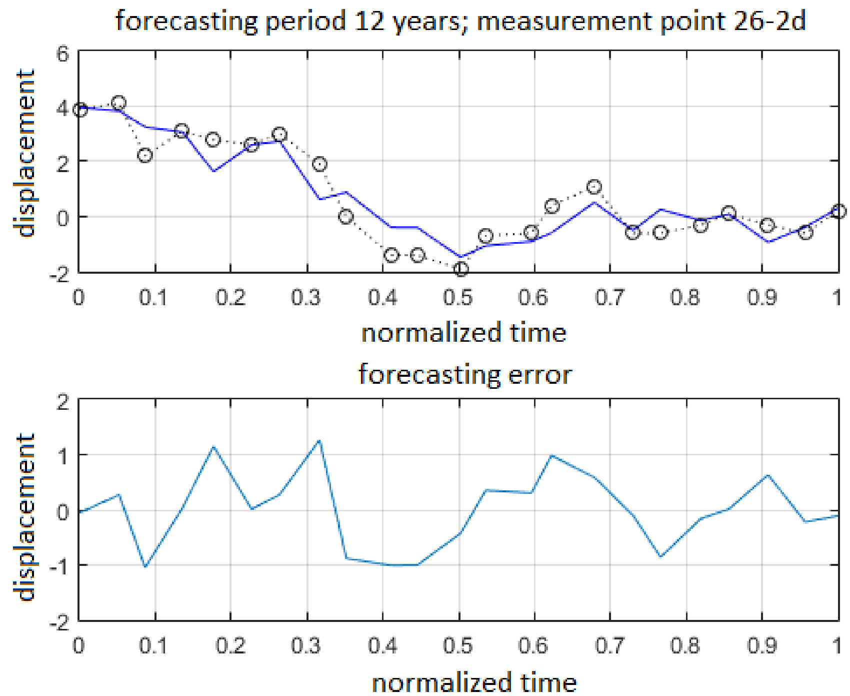

Figure 4. Approximation and approximation error, the body of the Solina Dam, measurement point no. 26-2d, forecasting period: 12 years.
Source: Own work.

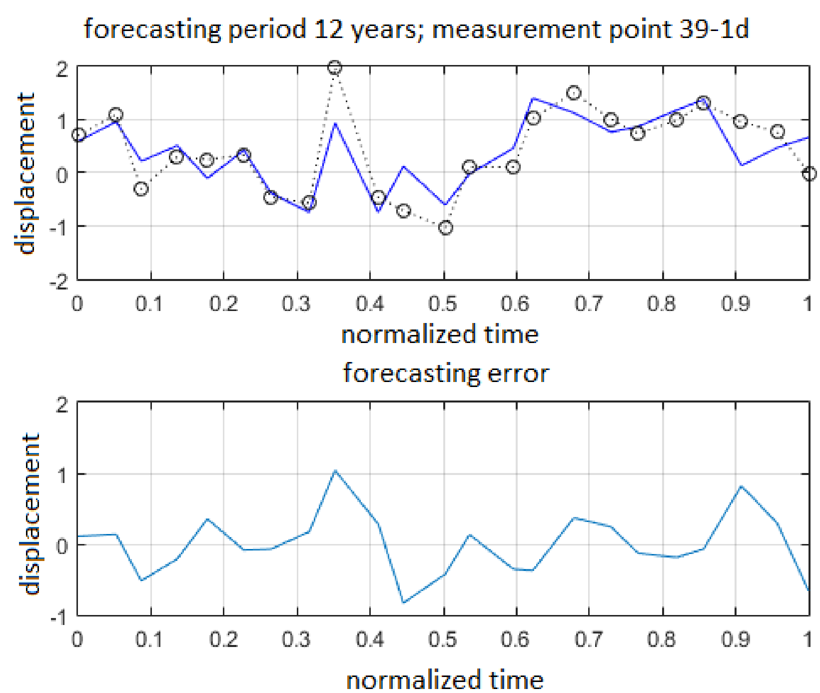

Figure 5. Approximation and approximation error, the body of the Solina Dam, measurement point no. 39-1d, forecasting period: 12 years.
Source: Own work.

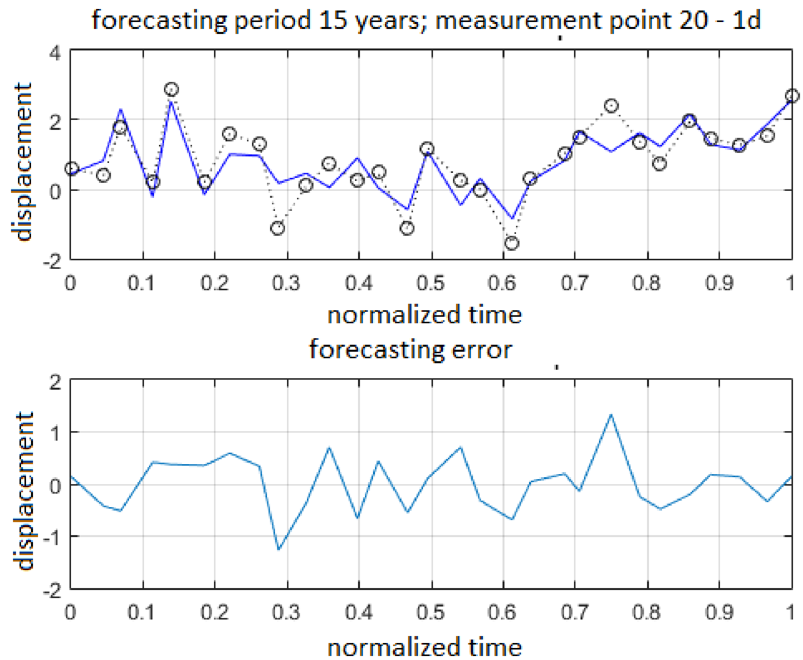

Figure 6. Approximation and approximation error, the body of the Solina Dam, measurement point no. 20 – 1d, forecasting period: 15 years. Source: Own work.

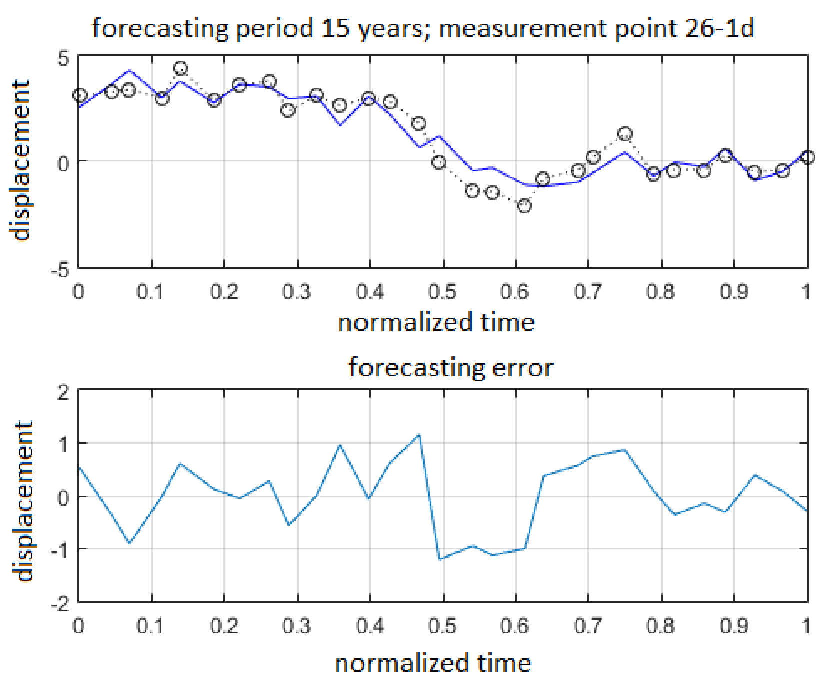

Figure 7. Approximation and approximation error, the body of the Solina Dam, measurement point no. 26 – 1d, forecasting period: 15 years. Source: Own work.

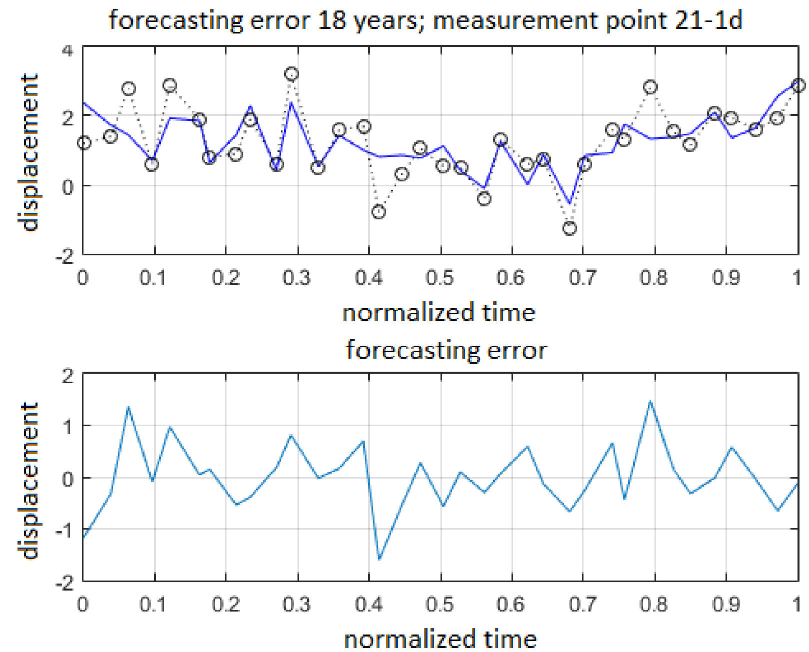

Figure 8. Approximation and approximation error, the body of the Solina Dam, measurement point no. 31 – 1d, forecasting period: 18 years.
Source: Own work.

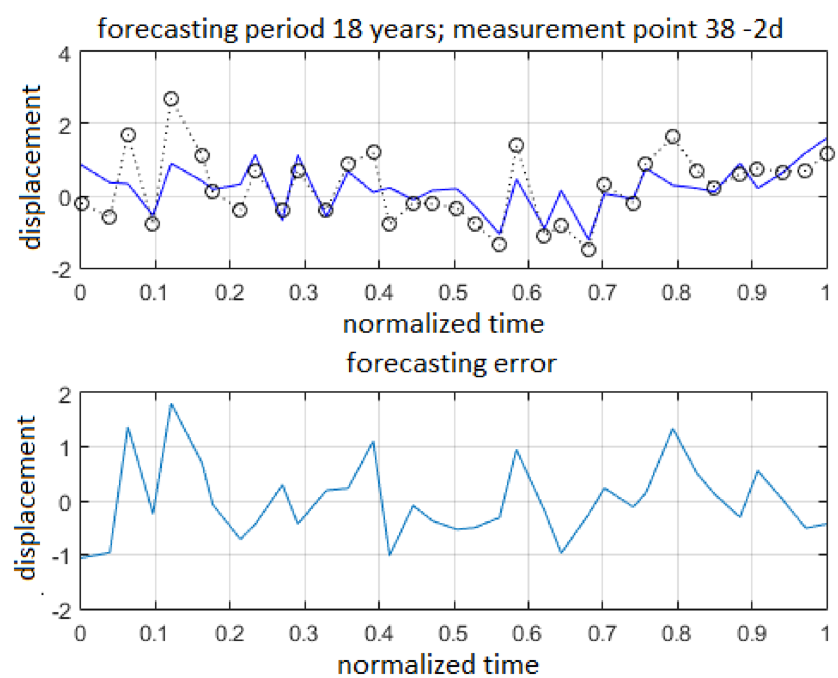

Figure 9. Approximation and approximation error, the body of the Solina Dam, measurement point no. 38 – 2d, forecasting period: 18 years.
Source: Own work.

4. DISCUSSION

The EDF model is one of the first statistical models created to support the interpretation process of the dam. Originally it was created to interpret the changes observed on the pendulums of arch dams. The model assumes the dependence between the movements of the object and variability of the air temperature, the water level and the impact of rheological factor. The simple formula of the EDF model entails numerous limitations. One of mentioned restrictions of chosen model is approximation of the influence of seasonality as a date function. However, previously conducted researches confirmed that using the actual values of the temperature did not improve the modeling of vertical displacements of the measurement points located on the dam. Other significant disadvantage of the EDF model is that it does not take into account the delay response between changes of the upper water level and the piezometers reaction. This fact makes many scientists exclude the possibility of using the EDF model as a tool of forecasting [7-9].

The EDF model, as one of the first statistical methods, is the basis for further modification of models to support analysis of the measurement data. Comparison of the coefficients of determination obtained for 4 different methods allowed for the conclusion that the EDF model is the best method to describe the behavior of the Solina Dam. Similar values of the coefficients of determination were obtained based on the HSTT model, however it was concluded that the EDF model better meets the assumptions of presented analysis [10-11].

5. CONCLUSIONS

National energy sector largely based on fossil fuels and increase in demand for electricity, points to the need to seek new energy sources. Undoubtedly, water is one of the sources of untapped energy potential resources. Its hydropower resources are only used in 12%. There are several reasons for that situation, among others it is the result of the limitations of formal – legal conditions, social disapproval and the needs of significant financial outlays. Despite these barriers several development strategies were proposed. Some of them are focused on modernization and renovation of existing hydrotechnical facilities. Solutions focused on ensuring stable share of existing hydraulic infrastructure in energy production indicate the need of verification of current state of the objects. Unfortunately, the technical condition of existing infrastructure is unsatisfactory; therefore, it is important to support the inspection process by interpreting data obtained from surveying also during the normal operation of the facilities. For this purpose, the EDF model was used to forecast the displacements of the Solina Dam. Previous analysis based on modeling of measurement data obtained from the body of the Solina Dam confirmed that the EDF model in good way reflects the behavior of the object. However, presented forecasting allowed for the conclusions that in case of points measured with frequency of 2 readings per year, data sequences corresponding to at least 15 years is required. Extension of the forecasting period from 10 to 18 years of exploitation significantly improved both the modeling and forecasting.

Both the presented analysis, as well as previously conducted researches were designed to support the control and safety of the power plant and collaborating with it dam. Presented measure will improve the safety of the object and the local residents, it also allows for a stable share of power plant in the national electricity production.

References

[1] T. Leszczyński Hydroenergetyka w Unii Europejskiej, *Biuletym Urzędu Regulacji Energetyki* 6 (2009).

[2] G. Kalda, Analiza stanu energetyki wodnej w Polsce, *Journal of Civil Engineering, Environment and Architecture* XXXI(61) (4/14) (2014) 81-92.

[3] K. Fiedler, Awarie i katastrofy zapór – zagrożenia, ich przyczyny i skutki oraz działania zapobiegawcze. IMGW (2007).

[4] P. Mazenot Méthode generale d'interpretation des mesure de surveillance des barrages en exploitation à Electricité de France, *Archiwum Hydrotechniki* (1974) 429-451

[5] Bąk Analiza przydatności modelu EDF dla celów monitoringu odkształceń elementów zapory Solina. IV Ogólnopolska Konferencja Młodych Naukowców „Nauka dla Środowiska Przyrodniczego", Poznań (2015)

[6] Instytut Meteorologii i Gospodarki Wodnej. Zapora Solina, wyznaczenie przemieszczeń. Warszawa (2011).

[7] S. Bonelli, P. Royet, Delayed response analysis of dam monitoring data. ICOLD European Symposium on Dams in a European Context, GEIRANGER, (2001).

[8] M. Kaniecki, *Rozwój energetyki wodnej na świecie i w Polsce*, Materiały szkoleniowe, Instytut Maszyn Przepływowych PAN, Gdańsk 2005.

[9] S. Bonelli, R. Tourment, H. Felix, Analysis of earthdam monitoring data. Selected problems of water engineering, Kraków, (2003) 133-150.

[10] L. Chouinard, R. Larivière, P. Côté, W. Zhao, Analysis of Irreversible displacements in multiple arch concrete dam using principal component analysis. Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montréal, Canada (2006).

[11] M. Majewski, The development of hydro power in Poland. The most important hydro engineering facilities. *Acta Energetica* 3(16) (2013) 45-53.

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