Introduction

The technical condition of dams and flood risk, which is inherent to the exploitation of such facilities are the result of the influence of multiple factors. Unsatisfactory state of hydraulic structures is confirmed by statistics conducted by numerous institutions, including the Chief Inspectorate of Construction Supervision [1]. The threat to the safety of dams are the rheological factors, excessive filtration through the ground, design and construction errors and difficulties to predict extreme natural phenomena [2]. These causes are the source of the occurrence of static and dynamic dam’s loads. These loads contribute to the creation of displacements and deformations observed in various parts of the objects. Growing experience of design engineers helps to minimize the risk of errors at the design stage, as well as eliminate mistakes in the execution phase. The greatest threat to the safety of this type of hydraulic facilities is currently incorrect exploitation. Independently of the data collected by various institutions and technological progress, one of the most serious threats are the unpredictable extreme phenomena. Even slight deformation of dam, which is compounded by the effects of natural factors can cause the failures of the object, the consequence of which is a flood, immense damage and loss of life. Current control and monitoring system also conductive the destruction of the dam. Therefore to improve the dam safety it is necessary to take measures to monitor the behavior of the dams. Monitoring and control system, which is currently used, is based on the regular geodetic measurements of each part of the object. To improve the safety of the dam it is necessary to take action on the interpretation of measurement data, that allow inferences about the technical condition of dams. Based on the data obtained during the routine operation of the dams we can infer about their technical condition. To this end they developed numerous methods of supporting the process of assessing the state of dams. These methods are focused on a variety of factors, from extreme phenomena, to natural cyclical factors, such as seasonal variation, the influence of time or cyclicity of temperatures.

This paper presents the methodology of assessing the impact of natural cyclical factors, but the primary aim is to assess the possibility of predicting changes in the structures as a result of the normal exploitation of the object. To evaluate the effects of natural factors on the movements observed on the dam, it has been created a number of methods which were supposed to eliminate the impact of rheological changes (the influence of time) and to analyze cyclical changes in shifts of the dams. Primary methods were based on the graphic elimination of the influence of rheological factors, due to their labor intensity they were displaced by statistical methods [3]. All of them are based on an a priori assumption of forms depending on the correlation between environmental factors and the measured values of deformation using a method of estimation of the mean. One of these methods is the model proposed in 1958 by Électricité de France. This model focuses on assessing the impact of the effect of the reservoir level, time drifting and the seasonal effect. The development of statistical methods has contributed to the extension of the model with additional explanatory factors. This paper as a continuation of previously conducted analysis also based on the model proposed by Électricité de France. Previous analysis [4] assessed the possibilities for adapting original EDF model on example of the Solina dam. The model proposed by Électricité de France compared with the original statistical methods were considered for better reflect the impact of rheological changes, this was achieved through approximation course of temperatures using trigonometric 2nd stage. Many researchers

1 Aleksandra Bąk, AGH University of Science and Technology, Faculty of Mining Surveying and Environmental Engineering, Department of Environmental Management and Protection, Cracow, Poland, abak@agh.edu.pl
[5, 6] confirmed that the EDF model provides a reliable assessment of the impact of rheological factors on the dam. Adjustment which were made in the previous analysis allowed us to conclude that the model reliably shows the movement of observed also on the elements of the Solina dam. These conclusions allowed for the continuation of the analysis, and attempts to dam displacement prediction based on the explanations factors. Forecasting will improve the safety of the object, systematize and streamline the current system of monitoring and control of dams by extending it by a factor of prediction.

Materials and methods

Model proposed by Électricité de France shows dependency between natural, cyclical factors and state of the dam. EDF model is a simple regression model for analyzing pendulums of arc dams. Method developed in 1958 has also proved to be a powerful tool for interpreting the behavior of concrete dams. EDF model is based on three basic influences: the hydrostatic and thermal effect, and the influence of time. Model although widely used has several limitations. One of them is the fact that the model is a good tool for interpreting the behavior of dams however it is not a reliable tool for analysis hydraulic measurements. The reason for this is that model does not account for the phenomenon of delayed response of the piezometers to changes in the hydrological factor [6]. In the article [5] the authors analyzed the possibility of excluding factors with less impact. Analysis was based on Fisher's exact test. Important conclusions that were made on the analysis also involve in displacements of surface. This limitation was caused by the opinion that monitoring data in the dimension of 1–2 per year do not provide sufficient database for their evaluation. Additionally, the model takes into account the seasonal effect, this means that it is assumed constant thermal effect as a function of a date. In practice it is assumed that the environmental conditions in a specific day of the year are the same. Despite this limitation researchers find that the results of modeling in a good way interpret the behavior of dam [7]. In addition in this analysis, 3 methodologies were evaluated based on the EDF model for thermal factor. There were made comparison between calculations based on the actual values of explanatory factors and the processed approximate cyclic data. As a result of this comparison it was concluded that the slight difference indicates that there is no need for accurate data analysis. Because of limitations of the model there were also proposed a model to help estimate the delay effect of air temperature and comparing them to analyze seasonal and direct measurements. New model were compared to EDF model. The analysis did not reveal significant differences between the results obtained using the models [6]. Model is burdened with a numerous limitations, even though it was a continuation of research displacement of the Solina dam.

Considering these simplifications and approximations there were analyzed possibility of the prediction of vertical displacements of the measuring points located on the crest of the dam. This modeling was conducted taking into account the temperature changes based on the seasonal impact. This analysis, as a continuation of previous research, also based on monitoring data of the Solina dam. The aim of this analysis was to evaluate the possibility of prediction of deformation the elements of Solina dam. This dam is the largest hydro-technical structure in Poland. It measures 81.8 meters in height and create a lake whose surface area reaches over 8.5 sq mi. The capacity of the reservoir is about 474 million m³. The maximum depth of the Solina lake is 60 m. Construction of the dam Solina allowed to create in 1968 power plant. The power plant equipped with four Francis type turbine sets, which installed capacity of 200 MW, provides an annual production order of 112 GWh. This article is focused on assessing the possibility of forecasting movements of the crest of the Solina dam. Ability to match based on geodetic measurements of vertical displacements over the 1992–2011 year. Displacements were analyzed based on 22 measuring points located on the crest of the dam.

Previous analyzes showed that the model EDF in a good way describes the evolution of the displacements taking into account the assumed explanatory factors. Modeling benchmarks located on the crest of the Solina dam was constructed using MATLAB. Additionally, according to the assumptions of the model, there were taken into account the variation of measurements in the level of reservoir, the influence of time, and the impact of the seasonal variation, based on the annual and half-yearly sequences. Monitoring data made it possible to generate a data model with factors specific to the individual measurement points. Previously analysis based on EDF model, indicated a credible reflection of the dam behavior. These conclusions allowed us to make predictions point attempts, which was then evaluated for compliance with the test of
absolute deviation [8]. The commonly used test shows that in the interval \([\mu - 3\sigma, \mu + 3\sigma]\) is 99.7% of all observations. If the measurement differs by more than 3 standard deviations from the expected value, we can conclude that it is invalid due to incorrect definition of the dependent values or to an underestimation of the uncertainty of measurement. Forecasting, similarly to the previous part of the analysis was based on measurements of vertical displacements of 22 measuring points located on the crest of the Solina dam. In order to provide a sufficiently comprehensive database further analysis was based on forecasting periods of 10, 12, 15 and 18 years of exploitation of the object.

Analyzing each of the benchmarks in individual periods forecasting by introducing the MATLAB variable data sequences allows to create specific model to each point. The aim of analysis was to evaluate the possibility of prediction, which was generated using designed model displacement value in the next measurement period in order to verify the continuity of the behavior of the dam. For this purpose, the displacement value were modelled, for each of the benchmarks and specified periods with established environmental conditions. Comparison of variables forecasting periods allowed for assessment of required size of database to obtain a reliable reflect the behavior of the dam.

Results

An important advantage of EDF model is the ability to identify and eliminate faulty instruments, and incorrect readings. This advantage of the model were used before the main analysis. As already mentioned forecast movements of points located on the crest of the Solina dam was made on the basis of 4 different forecasting periods. Modeling based on the 10 years of exploitation of the dam in the best way reflects the behavior of the dam in of the benchmarks number 1, 2, 3 and 4. Although the model well reflect the displacement of the dam, a 10-year base period made it impossible to forecast the next measurement period. The worst match was observed in the benchmark number 9, but the forecast in the next measurement period are consistent with the actual values of displacements.

Fig. 1. Approximation of displacements observed in the benchmark number 4 using the EDF model, forecasting period: 10 years.
Source: Own work.
Fig. 2. Approximation of displacements observed in the benchmark number 9 using the EDF model, forecasting period: 10 years.
*Source: Own work.*

Increasing the forecasting period of two years from the previous analysis model also find it very easy to reflect movements observed on the benchmarks number 1–4, similarly, small mean squared error was observed at the benchmarks number 5, 6 and 7. The worst matching was observed for the measuring point number 22, however, matching errors compared to the previous model are much smaller. Forecasts compartments in the case of 21 benchmarks are correct only in the case of measuring point number 16 prediction interval does not match the actually observed displacement.

Fig. 3. Approximation of displacements observed in the benchmark number 2 using the EDF model, forecasting period: 12 years.
*Source: Own work*
The analysis is based on 15 years of forecasting period largely coincides with modeling based on 12 years of exploitation. The best fit to the model displacement observed on benchmarks number 1 and 2, the worst reflection of the model again was observed in points 21 and 22. Increasing the forecasting period to 15 years made it possible to make interval prediction 100% compatible the actual displacement observed on the benchmarks located on the crest of the Solina dam. Assuming such an extensive period of forecasting predictions point are very close to the actual displacements the crest.

Fig. 5. Approximation of displacements observed in the benchmark number 1 using the EDF model, forecasting period: 15 years.
*Source: Own work*
Fig. 6. Approximation of displacements observed in the benchmark number 21 using the EDF model, forecasting period: 15 years.

*Source: Own work*

The longest forecasting period which was analyzing in this paper was 18 years. Based on those monitoring data again displacement of the benchmarks number 1 and 2 are best reflected by the EDF model. Matching the measuring of the points number 21 and 22 was the worst, but this error did not result in disturbances of forecasts. All of the points prediction based on 18 years of exploitation of dam allowed to achieve the forecast error smaller than 0.1mm.

Fig. 7. Approximation of displacements observed in the benchmark number 2 using the EDF model, forecasting period: 18 years.

*Source: Own work*
These results confirm that the EDF model although originally designed for arch dams, is also very good tool for analyzing the behavior of the dams of another types. The analysis also allows to conclude that the model may be useful to predict future movements, but in this case it is important to remember about the limitations resulting from the model. In this analysis were used 4 different periods of forecasting for the purposes of assessing the conditions of prediction. The shortest of analyzed periods has 10 years. The analysis showed that this is too short sequence of data, which made it impossible to predict future displacements of the measured points at the crest of Solina dam. Similar conclusions were made in case of forecasting based on the exploitation of 12 years. Only modeling database corresponding to 15 years of exploitation of the dam, assuming two measurements per year, allows to create a reliable in view of predictions model. Prediction interval based on the 15 - year of using the dam reflect the actual displacement observed for all benchmarks located on the crest of the dam. The longest period of time, which was analyzing in this paper was 18 years. Such extensive database allowed us to make point prediction, for which the error for each of the analyzed measurement points is not greater than 0.1mm.

**Discussion**

Deformation of dams can have multiple causes: from the most difficult to predict extreme natural phenomena, to small changes as a result of exposure to excessive filtration, errors during the design and operation and others. However, irrespective of potential risk factor acceded to the opinion that significant damage of dams are often the result of the increase of pressure in the pores, as well as the formation of cracks. Therefore, monitoring of dams and their control is really important in ensuring the safety of such facilities. The article rated the possibility of expanding activities relating to the interpretation of the displacements of the elements of Solina dam, based on the model EDF. Taking into account cyclical environmental factors, which included seasonal variations in temperature and level of reservoir allows to conclude about the current condition of dams and allows for an early response in the event of an intensification of displacements. Most of the studies confirmed the effectiveness of the model in terms of significant damage of the dams. Ultimately, the model has been created to analyze arc dams, but it also useful tool in evaluation of technical state of other types dams. Unfortunately the model has also faults and limitations, it is widely believed that statistical models which describes the dependence between the causes and quantitative effects have a number of weaknesses. Quoted analysis indicate that model has significant filtration defect. EDF model is not taken into account delays resulting from the reaction of structures on the measurement of explanatory factors. To solve problem of delays the authors proposed the delay analysis using a method based on Darcy’s
law and Richard’s equation. This solution included the use of a linear dynamic system share analysis factors that cause aging dams on the change of pore pressure. In addition, as a result of analysis, the authors ruled out the possibility of applying the model to predict. The reason for this limitation is difference in pore pressures and the lack reflect the effects of precipitation. A similar conclusions have made the author of the analysis presented in the article Delayed response analysis of dam monitoring data [6]. The authors support the lack of opportunities predictions based on the EDF model. The main cause of the phenomenon is also considered to delays as a result of distracting behaviors, such as filtering or viscoelasticity. As a solution they proposed to include in the statistical analysis an impulse response other than the aging of materials. Despite these limitations, the EDF model is considered to be stable and gives reliable results. This article represents an attempt of predictions with taking into account all restrictions and limitations which have burdened the model. Implementation of measures of this type makes it possible to improve the system of control and monitoring. This kind of action raises also the safety of local residents, allows for early detection of anomalies and discontinuities in the behavior of the dam.

Conclusions

Analysis which was taken are a continuation of the previous modeling of displacement of 22 measuring points located on the crest of the Solina dam. Forecast based on displacement data measurement points were continued based on EDF model. It is assumed correlation between displacements observed on the elements of the dam, and the cyclical natural factors. It is estimated that the greatest influence on the behavior of the dam has the thermal factor, seasonal variations and the influence of time. Despite restrictions and limitations which have burdened the model, the attempt of predictions were made. Restrictions which include the fact that the model does not take into account delays associated with response of weather conditions to the elements of the object. Other limitation is an approximations related to the establishment of permanent conditions for identical days. Analyzing of 4 different forecasting periods for comparative purposes has prompted to the obvious conclusion that the model best reflects the behavior of the dam when the forecast period minimum 12 years. Predictions based on a minimum service life of 15 years give reliable results of displacement measurement points using test of absolute deviation. Using the 15-year forecasting period allows for 100% consistency between prediction point and the actual displacements observed on the benchmarks located on the crest of the dam. The primary objective of the analysis was to evaluate the possibility of modeling the impact of cyclical natural factors, such as influence of time, hydrostatic effect which accounts the variation of measurements in the level of the reservoir and medium temperature displacements observed on the crest of the Solina dam. This analysis confronts the problems of the unsatisfactory condition of the dams and urgency to minimize the threat posed by their exploitation. To achieve this it is necessary to take measures to improve the safety of hydraulic structures by improving the control and monitoring of dams. Forecast displacements of the crest of the Solina dam is only a beginning for further study. It is planned in the following steps analysis of predictions the displacements of other parts of the dam. A holistic model will be created based on the displacements models and forecasts of individual elements. This model will allow treatment facility in a holistic manner, and thus allow to assess the condition of the dam. Implementation of the presented procedures will allow for early detection of disturbing phenomena of destructive processes or discontinuities in the movements of dams, significant evolution, irreversibility and other relevant disorder. It will also allow for an assessment of the current state of hydrotechnical object, as dams. It also greatly improve the decision-making process and indicate the necessary renovation and corrective actions or the necessity to take measures emergency protection. It helps also taking expertise, technical and economic analyzes.

Abstract

The EDF model shows dependency between the variation of measurements in the level of the reservoir, medium temperature and influence of time to the displacements observed on the crest of the Solina dam. Previous analysis showed that the model accurately reflects the movement of the crest of the dam, therefore further action was taken towards the prediction of the behavior of the object. The analysis was based on 22 measuring points located on the crest of the dam. Forecast movements of points located on the crest
of the Solina dam was made on the basis of 4 different forecasting periods. Only modeling database corresponding to 15 years of exploitation of the dam allows to create a reliable predictions. Implementation of the model which was proposed in the article will allow the interpretation of measurement data. These measures makes it possible to improve the safety of local residents, allows for early detection of anomalies and discontinuities in the behavior of the dam.

**Keywords:** EDF, monitoring and control of a dam, dam safety, displacement prediction, deformation modelling

**OCENA MOŻLIWOŚCI PROGNOZOWANIA ODKSZTAŁCEŃ ZAPORY SOLINA W OPARCIU O MODEL ÉDF**

**Streszczenie**

Model ÉDF uzależnia zachowania elementów zapór od zmiennosci poziomu zwierciadła wody górnej, cykliczności temperatur oraz wpływ czasu. Użycie modelu w obrazowaniu przemieszczeń korony zapory Solina dało zadowalające rezultaty, dlatego też podjęto się dalszych działań w kierunku predykcji zachowań budowli. W ramach analizy wykonano prognozę przemieszczeń dla 22 punktów pomiarowych zlokalizowanych na koronie zapory Solina. Predykcja w oparciu o 4 różne okresy prognozowania pozwoliła na wywnioskowanie, iż dla uzyskania wiarygodnych prognoz niezbędna jest sekwencja danych na podstawie 15 lat eksploatacji obiektu. Zastosowanie tak obszernej bazy danych umożliwiło uzyskanie pełnej zgodności pomiędy wartościami modelowanymi i obserwowanymi przemieszczeniami w obrębie określonych przedziałów ufności. Wdrożenie modelowania zaproponowanego w artykule pozwoli na interpretację danych pomiarowych oraz wnioskowanie o zmianach zachodzących w zaporach. Działania te pozwolą na bieżącą ocenę stanu technicznego zapór, usprawnienie procesu decyzyjnego oraz wskaż konieczne działania naprawcze i renowacyjne.

**Słowa kluczowe:** zapora Solina, modelowanie, przemieszczenia, korona zapory, ÉDF

**References**


