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Analysis of Changes in the Trends Recorded in Piezometers of the Solina Dam in the Study Period 2010–2015

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ABSTRACT

This paper aims to analyze the changes in the trends of water levels in closed piezometers installed in the largest dam in Poland, i.e. Solina Dam located in the Podkarpackie province. The scope of the research includes the analysis of water levels in piezometers in the study period between 2010 and 2015. Statistical tests for identifying and rejecting outliers were performed before carrying out the analysis of the data acquired from the Automatic Technical Dam Monitoring System including: two variants of the Q-Dixon's test (denoted as N9 and N13), as well as Grubbs' test and Hampel's test. A hypothesis was formulated that a change in the trend occurred after the flood in 2010. Using the least squares method , for each piezometer, two trend lines were matched to their water levels – the first one for the year 2010 and the second one for the period of 2011–2015. In this way, two slope coefficients of the linear function were obtained, together with the estimation of their errors. These slopes were compared using a statistical parallelism test.

Keywords: concrete dam, trend line, safety of hydraulic structures, closed piezometer

INTRODUCTION

Structures that are used for storage, impoundment or transportation of water are vulnerable to various types of damage and disasters. According to Kledyński [2012], a construction disaster is "loss of stability of a building structure, its parts or foundation, preventing its normal functioning without reconstruction, related to the threat to the safety of people, property or the environment". Roughly 2.2% of all the dams built before 1950 have been destroyed, whereas as far as the dams built after 1950 are concerned – less than 0.5%. Statistics demonstrate that about 70% of dam disasters occur during the first 10 years of their use [Rak 2007].

Ensuring the safety of operation of impounding structures requires performing systematic control measurements [Lach et al. 2013]. One of the most common causes of dam disasters is excessive seepage, improper operation of drainage equipment, or the scour of soil material from dams or their foundations [Lach et al. 2013].

The basic forms of monitoring dams include, e.g. piezometric measurements, which allow for measurements of water levels in open piezometers, or measurements of water pressure in closed piezometers [Mirosław-Świątek et al. 2012]. These measurements enable to control seepage through an impounding structure, and thus to assess structure's performance [Kledyński 2011].

Piezometric monitoring also allows to identify the anomalies occurring in the dam [Lach and Opyrchał 2014]. Thanks to systematic measurements, it is possible to effectively prevent a potential disaster by activating warning systems or alarms, as well as to plan modernization of the structure in advance [Molski 2012].

Currently in Poland, the tasks and obligations related to ensuring the safety of impounding structure's performance, as part of technical and construction supervision, as well as principles of their proper use, are governed by two legal acts [Kledyński and Nachlik 2006]:

- *Construction Law* Act of 7 July 1994 (Journal of Laws of 1994, No. 89, item 414, as amended),
- *Water Law* Act of 18 July 2001 (Journal of Laws of 2001, No. 155, item 1229, as amended).

TECHNICAL SPECIFICATION OF THE STRUCTURE

Due to its parameters and intended purpose for energy and flood protection purposes, the Solina Dam belongs to the first class of importance of hydraulic structures [Kozicki 2011]. This gravity dam is a heavy, concrete structure with expanded expansion joints. The length of the dam is 664.8 m and the maximum height reaches 81.8 m. The width at the base is 56.85 m plus the turbine plate of 73.55 m, which totals 130.40 m. The dam is divided into 43 sections with an average section length of 15 m [Dziewiański 1992]. The dam's axis was refracted by a V-shaped arch.

The static cross-section of the object is triangular with a slope of the upstream face of the dam of 1:0.05 [Kozicki 2011]. The width of the dam at the ordinance datum of 422.4 m above the mean sea level is 6.70 m. At this level, there is the crest with the width of 8.80 m, which is a path for tourists visiting the dam. The cross-section of the dam was divided into four concrete zones [Dziewiański 1992]. There are four levels of galleries with a total length of 2073 m. Two of the four galleries are accessible to visitors. The volume of the dam is 760 000 m³. The analyzed structure has three 17.52 meters-wide spillway sections, located in the old river bed.

MATERIAL AND METHODS

This paper aims to analyze the changes in trends of water levels in closed piezometers installed in the Solina Dam. These changes in water levels were analyzed in 30 closed piezometers in the Solina Dam (18 piezometers located before the barrier and 12 piezometers beyond the barrier) over a period of 6 years (from 2010 to 2015), taking into account the flood that took place in 2010. For each piezometer, 2191 piezometric measurements were performed, totaling to 65 730 observations; 12 piezometers were excluded from the analysis, because no measurements were carried out in the analyzed period or incomplete measuring sequences occurred. The location of the piezometers is illustrated in Figure 1.

Prior to analyzing the piezometric data, three statistical tests were used to identify and reject outliers: two variants of the Q-Dixon's test (denoted as N9 and N13), as well as Grubbs' test and Hampel's test [Lach 2016]. As a result, a total of 1 382 observations were removed from the data set, accounting for 2.1% of all the results.

Using open source software package *Gretl*, the methodology of the analysis involved creating graphs of changes in water levels in closed piezometers, and then calculating trend lines for each piezometer using the least squares method. The least squares method allowed to find a straight line that would be best "adjusted" to the measurement points collected in the graph. Parameters of the straight line were selected so that the sum of the squares of differences between experimental values y_i and calculated ones $a_i x + b_i$ was as small as possible. In this way, the value of the slope coefficient *a* and the intercept *b* were obtained.

Graphs for 30 closed piezometers were drawn, which illustrated the variability of the water levels over the 6-year period and adjusted trend lines with a variable coefficient *a*, taking into account the time before and after the flood in 2010. For each piezometer, $\hat{y}_1 = a_1 x + b_1$ and $\hat{y}_2 = a_2 x + b_2$ were obtained, respectively.

Then, using *Gretl* software, linear regression functions (trend lines) with different coefficients *a* were compared for each piezometer before and after 2010. A test of significance for the hypothesis of equality of two linear regression coefficients, called the parallelism test, was used for this purpose [Greń 1975]. The hypothesis H_0: $a_1=a_2$ was formulated against the alternative hypothesis H_1: $a_1 \neq a_2$,. Then, for both trials, the sum of squares of deviations of regression from these straight lines was calculated according to the formula:

$$\sum_{i=1}^{n_1}(y_{i1} - \hat{y}_{i1})^2 \ oraz \sum_{i=1}^{n_2}(y_{i2} - \hat{y}_{i2})^2 \tag{1}$$

The value of statistic was calculated according to the formula:

$$t = \frac{a_1 - a_2}{S_{a_1 - a_2}} \tag{2}$$

where:

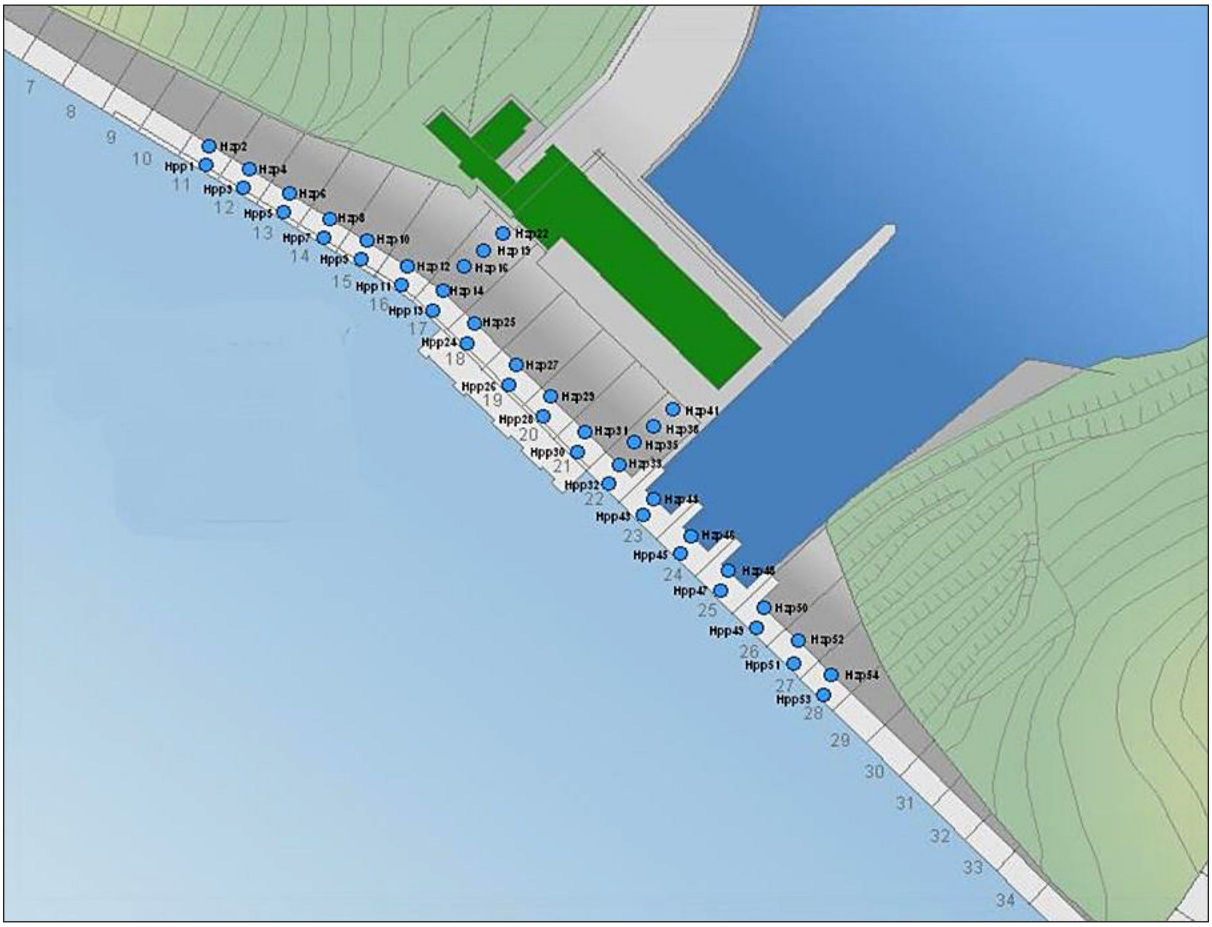

Fig. 1. Location of piezometers at the Solina Dam [Materials of the Group of Hydroelectric Power Plants Solina-Myczkowce]

$$S_{a_1-a_2} = \sqrt{\frac{\sum_{i=1}^{n_1}(y_{i1}-\hat{y}_{i1})^2+\sum_{i=1}^{n_2}(y_{i2}-\hat{y}_{i2})^2}{n_1+n_2-4}\left(\frac{1}{\sum_{i=1}^{n_1}(x_{i1}-\bar{x}_1)^2}+\frac{1}{\sum_{i=1}^{n_2}(x_{i2}-\bar{x}_2)^2}\right)} \quad (3)$$

Assuming that the verified hypothesis H_0 is true, the above-mentioned statistic has is characterized by t-distribution with ($n_1+n_2–4$) degrees of freedom. From the table of this distribution for a predetermined significance level of $\gamma = 0.05$ and for ($n_1+n_2–4$) degrees of freedom, such critical value t_γ was read so that $P\{|t|\geq t_\gamma\} = \gamma$. Comparing the calculated value of t statistic with the critical value t_γ, the following inequality was obtained: $|t| \geq t_\gamma$ lub $|t| < t_\gamma$. In the first case, the hypothesis H_0 was rejected, and in the second case there were no grounds for rejecting the hypothesis H_0.

RESULTS

Table 1 demonstrates the results obtained for closed piezometers of the Solina Dam. In addition, Figure 2 and Figure 3 illustrate exemplary time series for piezometer PZ118 for which the hypothesis H_0 was rejected, as well as piezometer PZ103 for which there was no basis for rejecting the hypothesis H_0.

CONCLUSIONS

Out of thirty studied closed piezometers of the Solina Dam, in eight cases there was no basis for rejecting the hypothesis of equality of slope coefficients of a straight line of regression before and after 2010. This means that the trend of water levels has changed for 73.3% of piezometers.

In most cases (81.8%) the trend is a declining one, which will lead to a decrease in filter gradients. For six of the analyzed piezometers (PZ104, PZ105, PZ109, PZ111, PZ113 and PZ122), the

Table 1. Results for closed piezometers of the Solina Dam in 2010–2015

Piezometer	Year 2010		Period of 2011-2015		Value S^2	Value S	Value t	Critical value t_γ	RESULT
	slope coefficient	coefficient b	slope coefficient	coefficient b					
PZ101	0.0013396	3.10767	-0.0001482	3.36150	6.52789E-09	8.08E-05	-18.4133	1.6456	Rejecting the hypothesis H_0
PZ103	-0.0000518	3.06605	-0.0000959	3.07535	2.47451E-09	4.97E-05	-0.8877	1.6456	No grounds for rejecting the hypothesis H_0
PZ104	0.0000411	0.08942	0.0000006	0.08603	2.21306E-11	4.7E-06	-8.5926	1.6456	Rejecting the hypothesis H_0
PZ105	0.0001648	0.84808	0.0000203	0.83186	3.06269E-10	1.75E-05	-8.2566	1.6456	Rejecting the hypothesis H_0
PZ107	0.0001021	1.57946	-0.0000066	1.58666	1.02573E-09	3.2E-05	-3.3940	1.6456	Rejecting the hypothesis H_0
PZ109	0.0003513	0.57136	0.0000199	0.61600	3.58504E-10	1.89E-05	-17.5062	1.6456	Rejecting the hypothesis H_0
PZ111	0.0001359	3.01645	0.0000894	2.94827	4.6854E-09	6.84E-05	-0.6799	1.6456	No grounds for rejecting the hypothesis H_0
PZ113	-0.0000525	1.05176	0.0002199	0.82334	3.24946E-09	5.7E-05	4.7781	1.6456	Rejecting the hypothesis H_0
PZ114	0.0000570	0.15962	-0.0000126	0.16488	7.5484E-11	8.69E-06	-8.0112	1.6456	Rejecting the hypothesis H_0
PZ115	-0.0000370	0.91346	-0.0000450	0.88043	3.8358E-10	1.96E-05	-0.4068	1.6456	No grounds for rejecting the hypothesis H_0
PZ116	0.0000282	0.72135	-0.0000276	0.69936	6.25679E-11	7.91E-06	-7.0563	1.6456	Rejecting the hypothesis H_0
PZ117	0.0000485	0.67890	-0.0000247	0.66504	5.63775E-11	7.51E-06	-9.7480	1.6456	Rejecting the hypothesis H_0
PZ118	0.0003151	5.73272	-0.0001063	5.85005	6.70784E-09	8.19E-05	-5.1450	1.6456	Rejecting the hypothesis H_0
PZ119	0.0000536	0.09099	-0.0000371	0.11409	3.17687E-11	5.64E-06	-16.1014	1.6456	Rejecting the hypothesis H_0
PZ120	0.0000320	5.73553	-0.0000729	5.70528	7.17233E-09	8.47E-05	-1.2381	1.6456	No grounds for rejecting the hypothesis H_0
PZ121	0.0001542	0.28070	-0.0000290	0.31591	1.5158E-10	1.23E-05	-14.8790	1.6456	Rejecting the hypothesis H_0
PZ122	0.0000340	5.34582	0.0000074	5.41900	9.16211E-09	9.57E-05	-0.2779	1.6456	No grounds for rejecting the hypothesis H_0
PZ123	0.0000656	0.22053	-0.0000211	0.24561	1.06237E-10	1.03E-05	-8.4194	1.6456	Rejecting the hypothesis H_0
PZ124	-0.0000277	4.98102	-0.0001166	5.00968	7.36601E-09	8.58E-05	-1.0363	1.6456	No grounds for rejecting the hypothesis H_0
PZ126	0.0002367	4.38403	-0.0000494	4.49121	7.72241E-09	8.79E-05	-3.2559	1.6456	Rejecting the hypothesis H_0
PZ128	-0.0001057	0.76141	-0.0000466	0.73307	1.45231E-10	1.21E-05	4.9101	1.6456	Rejecting the hypothesis H_0
PZ129	-0.0002586	0.93741	-0.0000543	0.87218	1.2016E-09	3.47E-05	5.8925	1.6456	Rejecting the hypothesis H_0
PZ130	-0.0003263	0.78660	-0.0000705	0.80332	1.802E-09	4.24E-05	6.0276	1.6456	Rejecting the hypothesis H_0
PZ131	-0.0000101	5.20453	-0.0000387	5.58572	8.16598E-09	9.04E-05	-0.3172	1.6456	No grounds for rejecting the hypothesis H_0
PZ133	0.0001113	4.97949	-0.0000744	5.02406	6.27627E-09	7.92E-05	-2.3439	1.6456	Rejecting the hypothesis H_0
PZ135	0.0000788	5.31844	-0.0000984	5.34645	6.22006E-09	7.89E-05	-2.2469	1.6457	Rejecting the hypothesis H_0
PZ137	0.0000568	5.28617	-0.0000771	5.22363	7.3489E-09	8.57E-05	-1.5625	1.6456	No grounds for rejecting the hypothesis H_0
PZ139	0.0000089	3.91617	-0.0001476	3.93517	7.60433E-09	8.72E-05	-1.7940	1.6456	Rejecting the hypothesis H_0
PZ141	0.0000220	3.56342	-0.0001295	3.57235	4.98697E-09	7.06E-05	-2.1445	1.6456	Rejecting the hypothesis H_0
PZ142	-0.0000123	0.01076	-0.0000004	0.00153	4.71411E-12	2.17E-06	5.4775	1.6456	Rejecting the hypothesis H_0

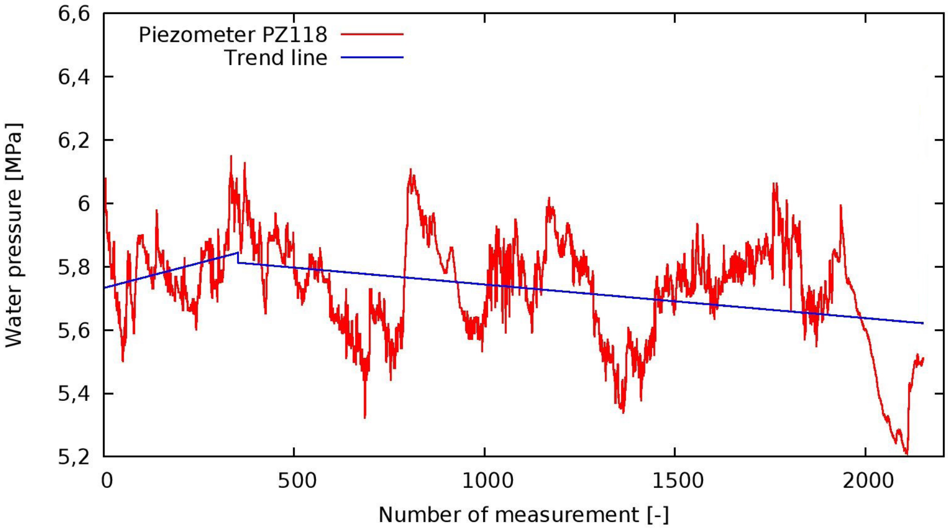

Fig. 2. Time series of changes in water levels in piezometer PZ118 along with the trend line for the Solina Dam in 2010–2015

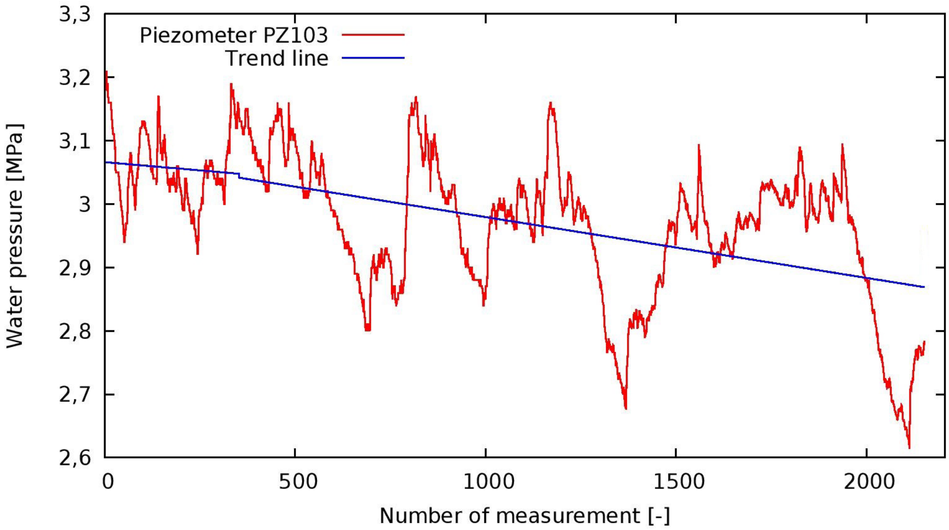

Fig. 3. Time series of changes in water levels in piezometer PZ103 along with the trend line for the Solina Dam in 2010–2015

trend after 2010 demonstrated an upward direction. These are the piezometers located in front of the barrier. The reasons for the noted changes in the trends of water levels and increase in filter pressure in these piezometers must be further clarified. Continuous monitoring of water levels, as well as possible model studies are necessary to explain this phenomenon.

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