NUMERICAL ANALYSIS OF PORE WATER PRESSURE CHANGES OF AN EARTH DAM AND MONITORING OF VERTICAL DEFORMATIONS. CASE STUDY - PLOPI DAM, IASI COUNTY

Isabela Elena BALAN[1], Denis ȚOPA[2], Flaviana CORDUNEANU[2], Ioan BALAN[3]
Loredana Mariana CRENGANIȘ[3]

e-mail: isabela.balan@yahoo.co.uk

Abstract

Numerical analysis of pore water pressure changes and the evolution of vertical deformations are the main aspects of the behaviour monitoring of an earth dam. This study analyzed the main aspects of the behaviour monitoring of the Plopi Dam, built on the Gurguiata River, in the northwest of Iași County, Romania. The main data taken into consideration are the dam body's type and material, the foundation's soils, and the dam's monitoring equipment. For tracking the evolution of the pore water pressure, 12 piezometers are used. The Plopi Dam is equipped with 19 piezometers, of which 9 piezometers (marked with B) show the route of the infiltration curve through the dam body and 10 piezometers (marked with F) have the bottom level in the base of the foundation and record the variation of groundwater levels in the aquifer. The paper presents the pore-pressure ratios in embankment material throughout its existence, mainly in the last 12 years, and the influence of external stresses on the hydrostatic levels. Data obtained for a period of 45 years (1978-2023) from 11 landmarks, placed on the dam canopy, were used in the settlement analysis of the embankment The filling in the dam body is still being consolidated, the settlements are significant, the pore pressures are high, so the monitoring of the dam's behaviour is done continuously so that the dam is safely exploited.

Key words: dam, pore pressure, hydrostatic level, settlements, consolidation

Dams are barriers to the river flow that are either constructed or natural. A dam is a hydraulic structure of impervious material built across a flowing stream, river, or water channel to create a reservoir of impounded water for such purposes as water supply, irrigation, hydropower, flood and erosion control, navigation, fishing, recreation, and other uses (Osuagwu J.C. *et al*, 2017).

The high risks associated with earth dams in operation may be mitigated by reliably, extensively, and resolutely checking the embankment and natural reservoir slopes behaviour, through the interpretation of monitored precursors and/or indicators, in order to promptly bring to light the presence of dangerous phenomena. The pore water pressures, the seepage flows, the displacements, and the total stresses are the typically monitored variables to ensure dam safety. Monitoring the surface displacements hence represents an effective tool to check the above mentioned risk phenomena, especially global instabilities within the embankment and reservoir natural slopes (Martire D.D. *et al*, 2014).

Vertical deformations of the embankment dams, if not effectively monitored, could be disastrous for the structural integrity of the dam (Osuagwu J.C. *et al*, 2017). Settlements may lead to dangerously diminished canopy levels, and thus result in dam overtopping, which could result in dam failure and complete washing away of the dam. Deformations of embankment dams have to be measured at least once every year. In this way, any sudden changes in settlement can be detected and a more detailed evaluation can be carried out. The monitoring data must be analyzed and evaluated continuously and presented graphically so that both long-term and short-term tendencies are visualized (Pytharouly S., Stiro S., 2008).

The dam of the Plopi reservoir, located on the Gurguiata River, is an earth dam that provides a global retention to the canopy of 11.293 million cubic meters (Water Basinal Administration Prut – Bârlad, 2022). The dam is made of earth, of homogeneous type, with a maximum height of 10.50 m and a crown length of 330 m and has a 1m high concrete parapet in the upstream part of the

[1] Water Basinal Administration Prut-Bârlad, Iași, Romania
[2] Iasi University of Life Sciences, Romania
[3] „Gheorghe Asachi" Technical University, Iași, Romania

canopy. Immediately downstream of the Plopi dam, the Huc buffer pond is located. The water level in Huc pond of 75.16 meters above Sea Level is 3.08 m below the established Normal Retention Level in Plopi reservoir (78.24 maSL). In the area of the dam's embankment, the soils consist, from a lithological point of view, of muddy clay soils, weakly consolidated, very compressible, and of very low load-bearing capacity, developed on thicknesses of 2-5 m. In most of the drillings carried out in the dam body, the groundwater was found at depths between 0.5 and 1 m from the surface of the land (*figure 1*).

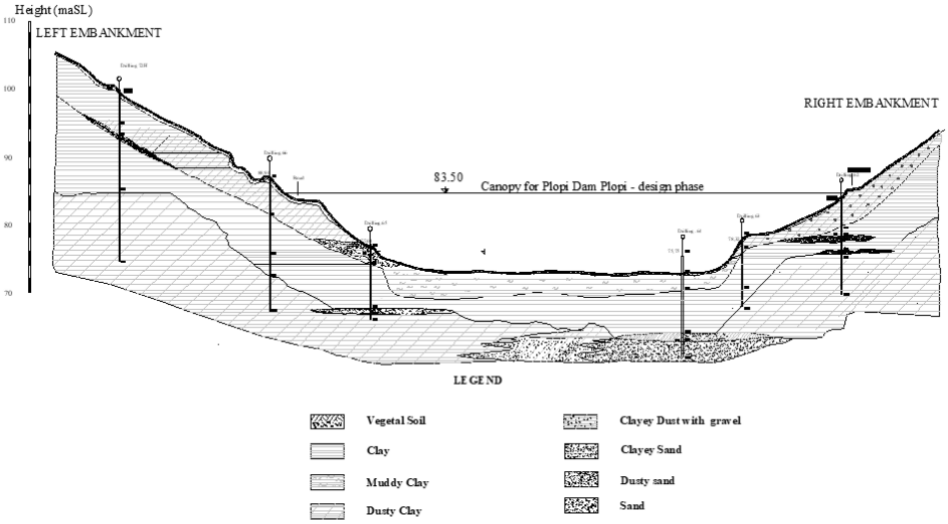

Figure 1 **Longitudinal section through The Plopi Dam foundation ground**

Based on laboratory analyses, from the early stages of design, it was established that the foundation ground, although compressible, still has sufficient load-bearing capacity to support the load transmitted by the weight of the dam. Also, from the early stages of construction of the dam, the layers presented important settlements, longitudinal cracks, tears, and movements of the fillings to the downstream. During construction, higher than expected construction pore pressures were experienced in the dam body. On completion of the embankment construction it was found that pore water pressures in the core were particularly high and that even at the lower elevations there had been very little dissipation of pressure.

The analysis showed that the pore pressures within the dam body are just within acceptable limits, but are dissipating far slower than had originally been envisaged.

The main component of dam behaviour monitoring is represented by the measuring installations for the dam response to stresses.

- For tracking the evolution of vertical deformations are used:
  - 11 vertical axis landmarks on the canopy of the dam
  - 2 fixed landmarks;
  - 2 landmarks on the operation tower;
- For tracking the evolution of body dam seepage there are 19 piezometers (9 piezometers marked with B are for determining the infiltrations through the dam body, 10 piezometers marked with F indicate the level of the water column resulting from the pores of the foundation ground). The piezometers are mainly distributed in 5 major characteristic sections, marked with S I – S V (*figure 2*).

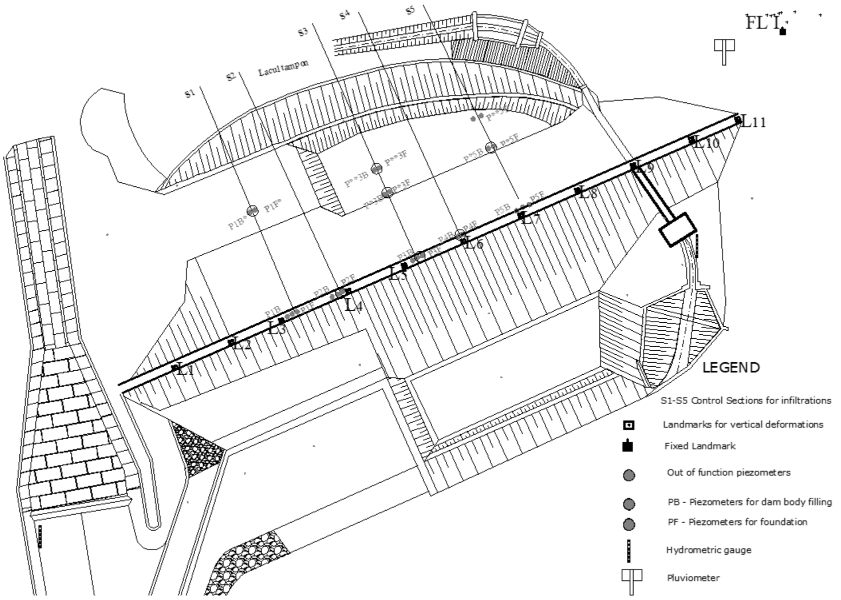

Figure 2 **The Plopi Dam plan view**

MATERIAL AND METHOD

1. Pore pressures

Most methods available to design engineers for predicting the development of pore pressures during and soon after the construction of earth dams use the approach that assumes the equality of pore pressure at a given point with a certain percentage of the over-burden pressure. Additional monitoring of pore pressures can prove necessary, particularly on high concrete dams. Measurement of pore pressures is recorded together with the water level in the reservoir (William P.J., 2004). Geotechnical problems that earth dams could experience during their operational stages are mainly related to slope instability and internal erosion phenomena (Jannati P., Mohammadi M., 2010). Dam loading history should be preventively known; in addition, monitored physical quantities and results from periodical inspections should be suitably collected and interpreted during the different stages of the dam's life (Nayebzadeh R., Mohammadi M., 2000). As consolidation of an embankment occurs, the excess pore pressures are dissipated. The pore pressure ratio is defined as the pare pressure at a given point divided by the overburden pressure above that point (*u/gh*). This ratio is dimensionless.

Bishop has noted that failure is likely to occur in a dam where the average pore pressure ratio throughout the entire cross-section of the embankment exceeds 0.60, *except* in the case of a low dam. For limited water content variation ratio is influenced by fill height which in turn reflects such factors as the length of the drainage path and the degree of saturation (Clough C.W., Snyder J.W., 1966). Infiltration and seepage analyses are important tool to assess the susceptibility of seepage failure in dams and to study the hydraulic conditions for analyzing the stability of dam slopes. Factors that affect the build-up of construction pore pressures are numerous. Placement water content, overburden weight, length of drainage path, rate of construction including construction stoppages, nature of the care material, and presence of drainage features all exert some effect. The seepage through an earth dam generally correlates with the reservoir water level of the dam. The seepage rate through a dam should be measured and used as a basis for a seepage stability evaluation (Lee J.-W. *et al*, 2018). The monitoring of pore pressure as well as water levels of an embankment dam to observe potential seepage problems is important; anomalies that are indicative of internal erosion problems should be detected in advance to prevent catastrophic consequences. Piezometers are the most commonly used instruments to monitor the water level in dams, which can often be used to compute pore water pressures (Crum D., 2011). According to Clough G.W., Snyder J.W. (1966), the research of several scientists, including Hilf J.W., concluded that for a dam that has no upstream sealing or impervious core, but has downstream drain blanket, the maximum pore pressure ratio in a dam body has a value between 0.4 and 0.65 (Clough C.W., Snyder J.W., 1966).

2. Vertical deformations

The study reviewed the main features of the embankment and instrumentation devices incorporated into the embankment to accommodate the prediction and analysis of settlement of the fill material and the bedrock in the post-construction era. The scope of this study was limited to the canopy of the dam because landmarks are only placed on the canopy. To calculate the percentage of the total elevation of the dam that settled at a section of the dam, the following equation is used (*eq. 1*):

$$P(\%) = \frac{s}{H_{total}\%} \qquad (1)$$

Where, *P(%)* is the percentage of the dam elevation that settled at a section, *s* is the actual settlement at the section and H_{total} is the total dam elevation. A dimensionless parameter known as the *Settlement index* was calculated for each of the eleven sections. Equation 2 is the equation of the settlement index as reported by Pytharouli S. and Stiros S. (2008):

$$S_i = \frac{s}{1000 \cdot H \cdot \log(\frac{t_2}{t_1})} \quad (2)$$

Where S_i is the settlement index, *s* is the canopy settlement measured in mm between the time period and since the completion of the embankment at a section of the dam meters high - *H* (Charles J.A., 1986). Values greater than 0.02 indicate that mechanisms other than creep or secondary consolidation of the embankment dam material contribute to dam settlements (Tedd P. *et al*, 1997). The settlement index is analogous to the coefficient of secondary consolidation for a clay soil. Pytharouli S. and Stiros S. (2008) identified the mechanisms other than the creep or secondary consolidation affecting crest settlement of the Kremasta Dam in Greece as:

1) Reservoir level fluctuation and
2) Rainfall

So, if the value of Si > 0.02, that means that other than creep or secondary consolidation, the other mechanisms mentioned above are responsible. Limit values are important to give a warning in an emergency situation (Charles J.A., Tedd P., 1991). The average settlement index at each section can be plotted against the time period to obtain a time series consisting of the values of the average settlement index for each of the sections.

RESULTS AND DISCUSSIONS

The analysis of the behaviour in time of Plopi dam was performed by examining the evolution of the response parameters (piezometer levels, infiltration flows, displacements) to the external stresses. The variations of the water levels in the reservoir, of the precipitations, and of the registered temperatures that acted on the reservoir and in the basin catchment had the main impact on the variation of the water levels in the piezometers and implicitly on the infiltration regime through the dam.

1. Pore pressures

For further study of the infiltration regime in the dam, the research focused on the hydrostatic levels in all of the piezometers (Section I-V) for a period of 23 years, with an accent on a shorter period of time, during the years 2012–2023 (*figure 3)*.

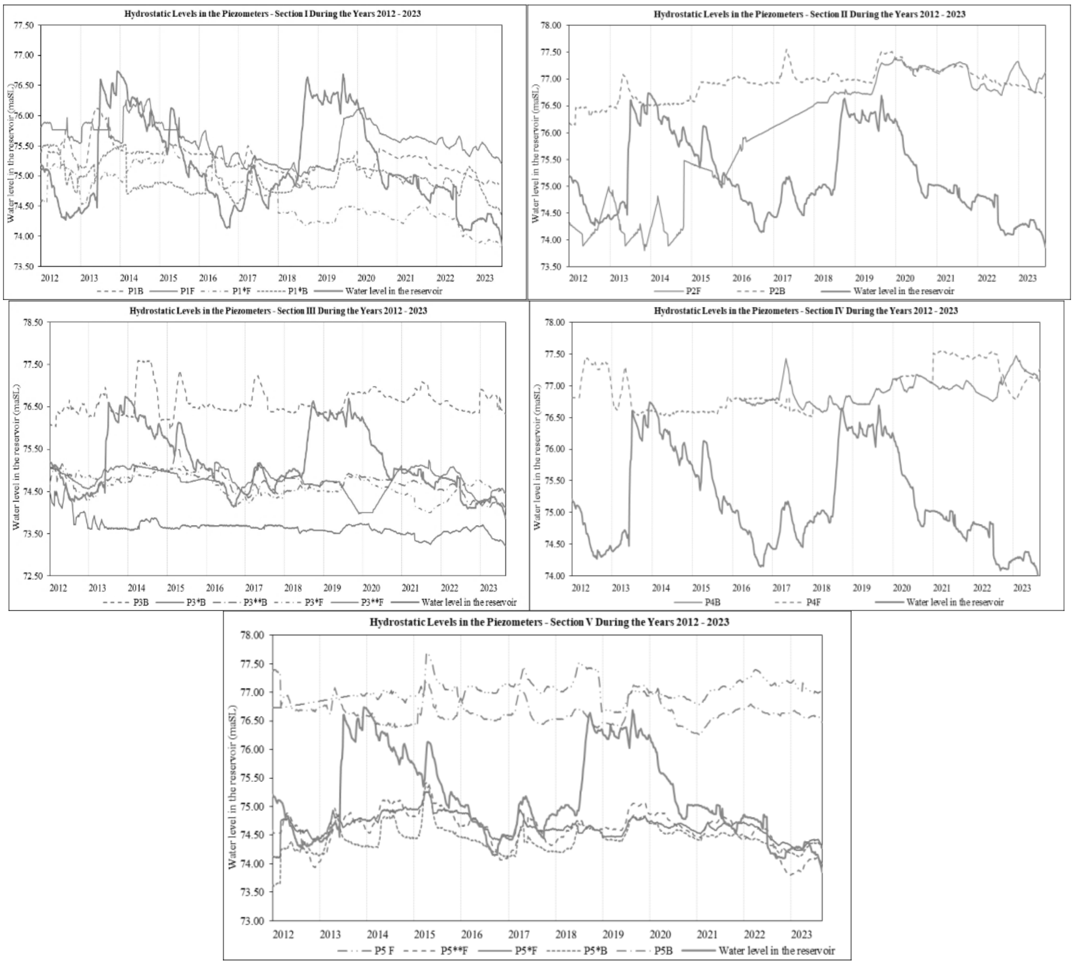

Figure 3 **Hydrostatic Levels in the Piezometers During the Years 2012-2023**

The behaviour monitoring of the dam is a very complex activity, performed by following the indications of specific legislation and technical regulations. Synthetic analysis for the behaviour monitoring of the dam in a given period of time formulates the conclusions regarding the overall exploitation of the dam and suggest the required works of rehabilitation, that may be imposed by the technical status of the hydro-technical construction.

Installed piezometers upstream of the dam body show a higher pressure than the downstream, due to the high saturation state of the phreatic line.

In Romania, the *Reports of Synthetis of Behaviour Monitoring of the Dams* are analyzed according to the specific regulations. In the year 2004, such Report was analyzed by a Comitee and the experts concluded: given that the dam was constructed on muddy clays, and that this is an important risk factor for the stability of the dam, the in-depth judgment of the measurement results of F-type depth piezometers was recommended, paying particular attention to the time variation of the measured values, in correlation with water levels in the reservoir. It was suggested that this follow-up be done on the basis of the *HILF criterion* (the ratio between the water pressure in the pores and the weight of the soil filling at the respective measurement point) by which, at a value of 0.5 it is recommended to enter the *attention phase* (Balan I.E., 2021). Therefore, the pore pressure ratios were calculated for each of the piezometers that indicate the level of the water column resulting from the pores of the foundation ground, and represented in *figure 4*.

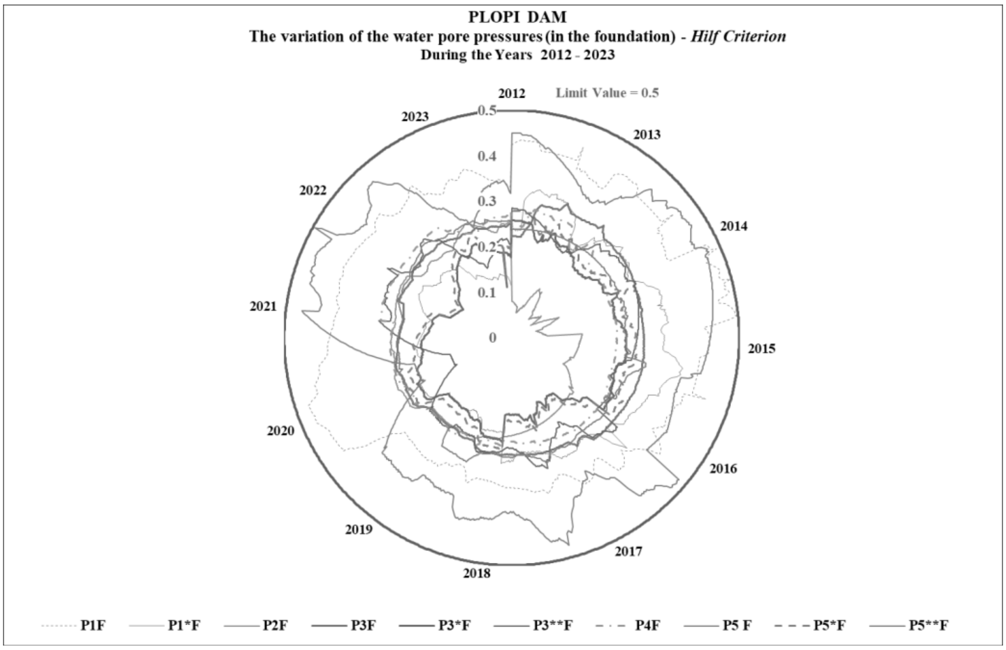

Figure 4 **The Variation of Pore Pressure Ratios during the Years 2012-2023**

The position and height of every tube, and the lower part of the piezometers were taken into account, along with the hydrostatic levels measured by the designated hydrotechnical agent. The calculated pore ratios were all drawn as point lines in one graph shown in Figure 5. It can be concluded that all of these piezometers have pore pressure ratios within the admissible range represented by the value of 0.5 that was set according to the *HILF criterion*. This analysis was only performed for a period of 12 years for which there was available the complete archive of hydrostatic levels. But the incomplete archive that was available for previous periods of time, also showed pore pressure ratios within the admissible range.

2. Vertical deformations

For the measurements of the vertical deformations, a Leica Geosystems Total Station was used. The measurements were taken on the vertical axis landmarks placed on the dam canopy, from 1978 to the year 2023. The average annual vertical deformation for the last 23 years is about 11.8 mm/year (*figure 5*).

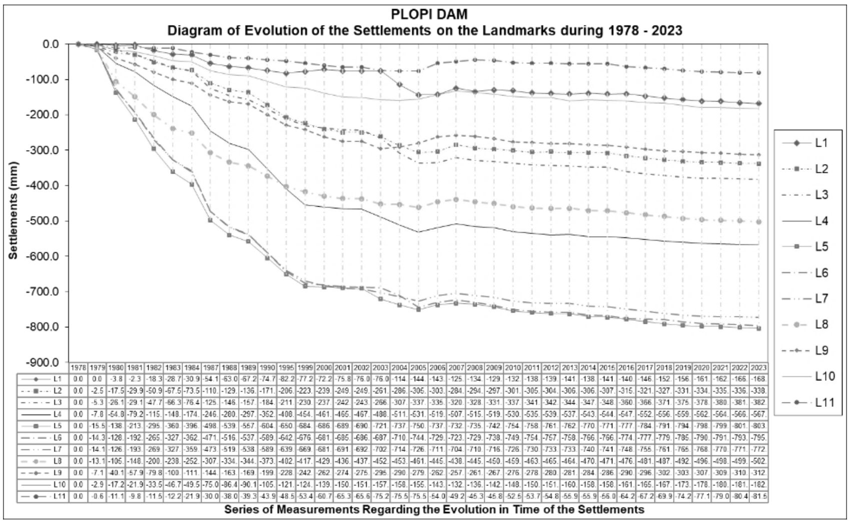

Figure 5 **Evolution of the annual vertical deformations on the L1-L11 landmarks during 1990 – 2023**

The maximum annual settlement, as measured by the landmarks, since the end of construction was about 113.8 mm in the central area of the dam (landmarks L6). The cumulative settlement of the crest, as measured by the landmarks, since the end of construction to the present time is about 803,8 mm, or 7.65% of the maximum embankment height, in the central area of the dam - landmarks L6 (*figure* 6).

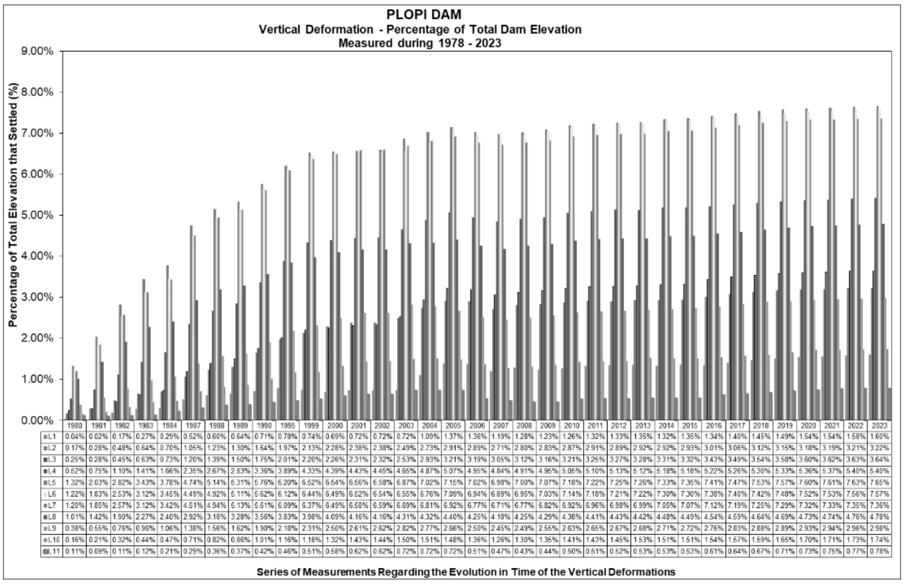

Figure 6 **Evolution of the Settlements on the Landmarks during 1978 – 2020**

The water level in Plopi reservoir hasn't fluctuated considerably throughout the years. Since the final impounding in the year 1984, the water level has mainly been near or below the Normal Retention Level established by design. The daily fluctuation rate has been below 50 cm/ 24 hours, so the water level hasn't influenced considerably the settlements of the dam (*figure 7*).

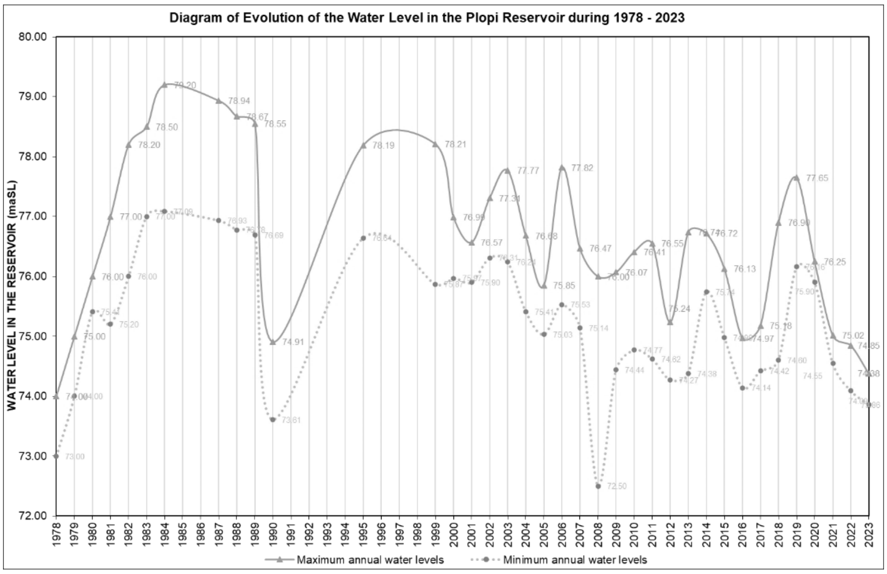

Figure 7 **Evolution of Water levels in the Reservoir during 1978 – 2023**

Settlement indexes S_i were calculated for all of the 11 landmarks, regarding the last 30 years of existence, for separate intervals of time of 5 years (*figure 8*). As seen in *figure 8*, the Settlement Indexes S_i calculated for the deformations measured during 1990 – 2023 are below the value of 0.02 which can indicate the fact that dam settlements are not affected by creep or secondary consolidation of the embankment dam material.

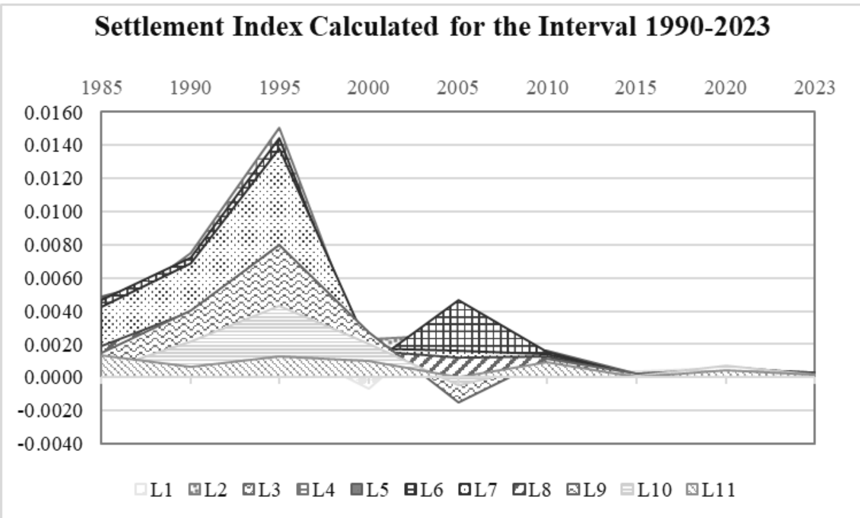

Figure 8 **Settlement Index Calculated for the Measurements on the Landmarks during 1990–2023**

The foundation ground, formed mainly by muddy soils, seems to have insufficient load-bearing capacity to support the load transmitted by the weight of the dam, and the groundwater was found at depths between 0.5 and 1.0 m from the surface of the land. From the early stages of construction of the dam, the layers presented important settlements, longitudinal cracks, tears and movements of the fillings to the downstream. The maximum values of the Settlement Indexes S_i were calculated for the deformations measured during the year 1990. The water level in Plopi reservoir had a significant variation during that year, as there was a difference of 3.6 m compared to the maximum water level values of the previous year. Therefore, it is found that the deformations of the earth fill are affected by the level fluctuations, and the Settlement Indexes S_i are directly influenced by the variation of the water level in the reservoir. The visual observations made by the exploitation personnel have not highlighted visible cracks, or tears in the dam body. It seems that the downstream Huc fishpond has contributed to a state of equilibrium of the dam, so the rate of annual settlement has gradually decreased in the last few years, even if the consolidation process continues.

The special monitoring activity showed that the Plopi dam is characterized by significant vertical deformations of the earth filling (maximum settlement 803.8 mm measured at the L6 landmark positioned in the central part of the dam), high infiltration levels and very high hydrostatic levels of the aquifer. However, considering the good behaviour of the dam since commission, it is generally agreed that the dam behaves properly, according to the general design predictions.

CONCLUSIONS

The objective of the study was to evaluate pore water pressure changes in Plopi Dam. The analysis of the behaviour in time the Plopi dam was performed by examining the evolution of the response parameters (piezometer levels, infiltration flows, displacements) to the external stresses. All piezometers had pore pressure ratios within the admissible range represented by the value of 0.5.

The Synthesis Reports of the Dam Behaviour Monitoring performed on an annual basis and the *Post-event Reports* elaborated after the occurrence of significant floods, atypical behaviours, incidents or accidents may highlight structural changes in the dam and adjacent hydrotechnical constructions. Subsequently, it is necessary to implement the maintenance, repair or rehabilitation works of the dam. We can conclude that, although the dam body hasn't fully consolidated nowadays, it is in good shape and can still very well ensure the retention of water in Plopi reservoir and can provide the designed flood protection. The intensive behaviour monitoring of the dam is done continuously with an increased degree of attention, according to the regulations for this type of earth dam.

It is necessary to continue the safe operation of the dam in accordance with the *Special Monitoring Project* (Water Basinal Administreation Prut-Bârlad, 2017) and the *Operating Regulations* (Water Basinal Administration Prut-Bârlad, 2016).

ACKNOWLEGMENTS

There was no external funding for this study. This study presents the results of a research project that took place at the "Gheorghe Asachi" Technical University, Iași and it could not have been made possible without the data provided by the Water Basinal Administration Prut-Bârlad.

REFERENCES

Balan I.E., Țopa D., Corduneanu F., Balan I, Crenganiș L., Dănilă A., Cucuteanu A., 2021 – *Monitoring and numerical analysis of pore water pressure changes in an earth dam. case study of plopi dam, Romania,* THE NATIONAL TECHNICAL - SCIENTIFIC CONFERENCE - the 20th edition - „MODERN TECHNOLOGIES FOR THE 3RD MILLENIUM".

Crenganiș M.L., Balan I., Giurma-Handley R.C., Marcoie N., Diac M., Cucuteanu A., Dănilă A., 2021 – *Settlement* m*onitoring of Embankments Dam: Case study of Plopi dam, Romania,* THE NATIONAL TECHNICAL - SCIENTIFIC CONFERENCE - the 20th edition - „MODERN TECHNOLOGIES FOR THE 3RD MILLENIUM".

Charles J.A., Tedd, P., 1991 – *Long term performance and ageing of old embarkment dams in the United Kingdom*. Transactions of 17th International Congress on Large Dams, Vienna, 2:463-475.

Clough G.W., Snyder J.W., 1966 – *Embankment Pore Pressures During Construction*, Technical Report 3:722, U.S. Army Engineer Waterways Experiment Station.

Crum D., 2011 – *Rogue Piezometers*, 31st Annual USSD Conference, 1591–1602.

Jung I.-S., Berges M., Garrett J.H. Jr, Poczos B., 2015 – *Exploration and Evaluation of AR, MPCA and KL Anomaly Detection Techniques to Embankment Dam Piezometer Data*. Advanced Engineering Informatics, 29(4):902-917.

Jannati P, Mohammadi M., 2010 – *Investigation of excess pore pressure of pore water created by earth dam in the clay core of earth dams under the influence of nucleus*. 9th Iranian hydraulic conference Tehran.

Martire D.D., Iglesias R., Monells D., Centolanza G., Sica S., Ramondini M., Paganoa L., Mallorquí J.J., Calcaterra D., 2014 – *Comparison between Differential SAR interferometry and ground measurements data in the displacement monitoring of the earth-dam of Conza della Campania (Italy)*. Remote Sensing of Environment, 148:58-69.

Nayebzadeh R, Mohammadi M., 2000 – *Static analysis of soil dams affected by clay core formation*. Proceedings of the 4th national civil engineering congress, Tehran.

Osuagwu J.C., Owakah A., Chukwuocha A.C., Ibeje A. O., 2017 – *Settlement Monitoring of Embankment Dams: Case Study of Gurara Dam, North Central Nigeria*. International Journal of Science and Engineering Investigations, 6(71):66-72.

Pytharouli, S., Stiros, S., 2008 – *Dam crest settlement, reservoir level fluctuations and rainfall: evidence for a causative relationship for the Kremasta Dam Greece.* Proceedings on 13th FIG symposium on deformation measurement and analysis and 4th IAG symposium on Geodesy for Geotechnical and Structural Engineering.

Tedd P., Charles J.A., Holton I.R., Robert Shaw A.C., 1997 – *The effect of reservoir drawdown and long-term consolidation on the deformation of old embankment dams*. Geotechnique, 47(1):33-48.

Water Basinal Administration Prut – Bârlad, 2016 – *Special Monitoring Project of the Plopi reservoir*, Iasi (in romanian).

Water Basinal Administration Prut – Bârlad, 2019 – *Synthesis Report for the Behaviour Monitoring of the Plopi reservoir*, Iasi (in romanian).

William P.J., 2004 – *Masjed-e-Soleyman Dam instrumentation*, Halcrow Group Limited 5, Long-term benefits and performance of dams. Thomas Telford, London.