11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Monitoring of tailings dam built over tailings pond

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Abstract

Metallic mineral mining in R. N. Macedonia, as an industry with long tradition, deposits huge quantities of the ore processing remains in tailings dams. Some of those are examples of complexity: there is one which is being built cascading – one next to other along river valleys, while other one with its tremendous height – more than 100 m. The latter one is also specific for its building model: in a period of about 30 years, i.e., up to reaching height of 90 m, it was built with downstream method, while in the past 15 years, i.e., up to height of 134 m, an upstream method was applied, thus the tailings dam was positioned on top of the old tailings pond. Particular attention has to be paid to its monitoring, having in mind the two other very important elements related to its location: it is placed above rural settlements and in an earthquake prone area. For that purpose, both the national regulation, international experiences and results from numerical models for the vertical expansion of the tailing dam were followed when designing the monitoring system. It consists of inclinometers, piezometers, seismometers, surveying system and frequent field investigations and laboratory tests. Due to the specific circumstances of typical growth of the tailings dam and the long period of monitoring, it is obvious that some of the installed equipment is in continuous exploitation, some is extended, while some is replaced. From timeline point of view, some of the equipment is monitored occasionally or after extreme events, while other equipment is monitored in defined periods. This paper aims to digest the experiences of geotechnical and geodetic monitoring of the tallest tailing dam in R. N. Macedonia built using this specific combined method, and expose the findings obtained by different techniques.

Keywords: Tailing Dam, Monitoring, Inclinometers, Surveying System.

1. Introduction

Auscultation of tailing dams (TD) involves visual observations and measurements, which include geodetic, geotechnical and seismic monitoring. "Topolnica" TD, within the copper mine "Buchim", in Macedonia is build along the river Topolnica, above the village of Topolnica, in a seismically active region. Its purpose is depositing the flotation tailings and accumulating part of the flowing river water to be used as the technological water. Its initial design height of 90 m – achieved with downstream method – has been raised so far in two stages on the upstream side: it the first stage (until the beginning of the 21st century), up to 110 m, while the second stage is in progress and its current height is 134 m.

Due to specific conditions and long time span, monitoring of "Topolnica" TD has been regularly organized. Namely, the tailing dam operates with its own monitoring system since 1986, with the main goal to obtain reliable data on displacements and pressures that would develop in TD and to compare them with the design values. Measurements can play an important secondary role in providing a clear picture of behaviour of the TD and the tailing lake area as a starting point for the analysis of any challenge that may arise during the operation of TD, in order to undertake appropriate measures to manage any kind of risk. A third and very important goal is to advance the tailing dams designing technique using monitoring data.

The monitoring in recently created conditions is largely performed by the Faculty of Civil Engineering – Skopje (FCE). Thus, the *Design for technical monitoring of the Tailing Dam "Topolnica" at the mine "Buchim" - Radovish during the construction of a sand dam up to 654 meters above sea level* has been prepared in 2008 by FCE, in accordance with the *Rulebook on minimum required works and measures for technical monitoring of dams whose accumulations and tailings dams are above populated areas or commercial buildings of public interest.*

2. Monitoring system

The monitoring design defines methods and procedures of monitoring, number and type of devices and equipment used, the layout of measuring points, the scope and dynamics of measurements, as well as the criteria for evaluating the allowed changes in measuring values. Measurements at predefined time intervals include the measurement of: the water level in the basin, the water level in the piezometers, the water discharge in the drainage collector and nearby springs, the displacements in depth in the inclinometers, the geodetic surveying and the measurements of seismic activity. Due to a large volume of data and limited space, the following pages include a brief review of geotechnical and geodetic monitoring, with emphasis on measuring points indicated in Figure 1.

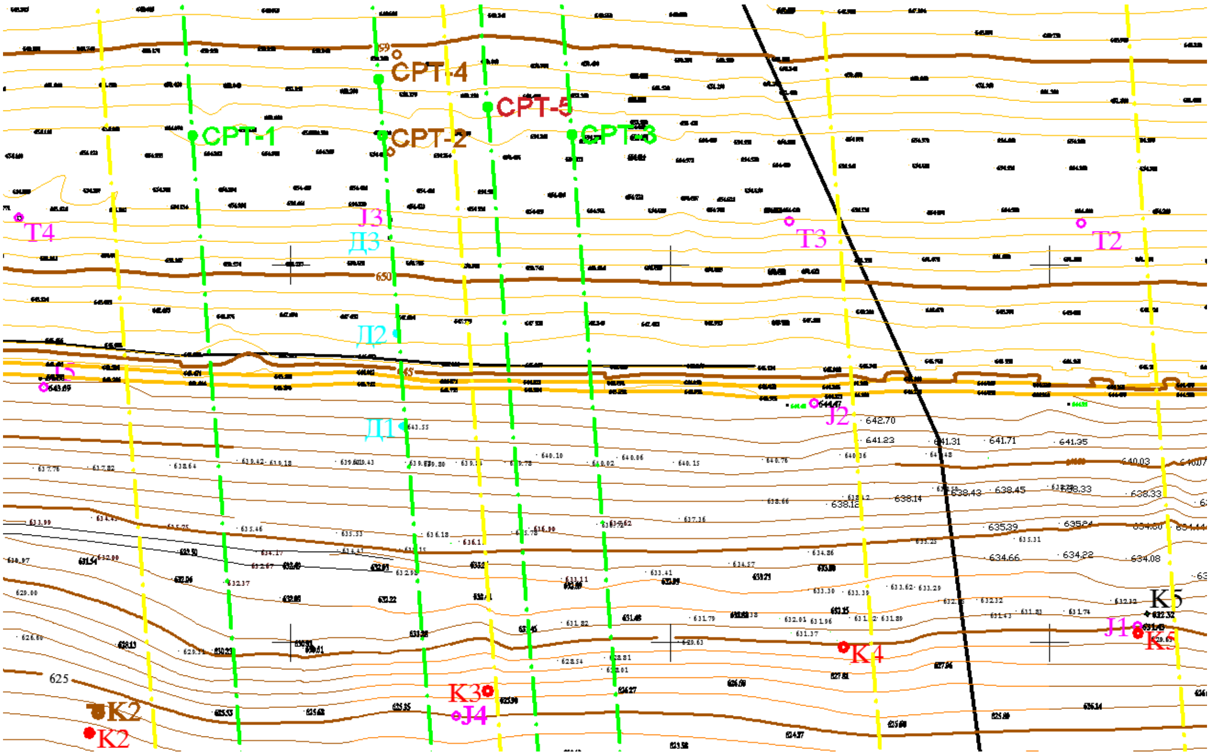

Figure 1: Layout of inclinometers J1, J2, J3, J4 and J5 and geodetic surveying points T_2, T_3 and T_4.

2.1 Inclinometers and methodology

After the tailing dam has reached its maximum height in May 2012, the monitoring system was updated with five inclinometers to monitor horizontal deformations in the body of tailing dam and six piezometers to monitor the groundwater levels. Their location is shown in Figure 1, and the characteristics are given in Table 1.

Inclinometer label	Elevation of the top of the inclinometer casing [masl]	Length [m]
J1	630.73	58
J2	643.76	66
J3	653.00	85
J4	625.00	54
J5	642.94	70

Table 1: Characteristics of analysed inclinometers.

Zero measurement of inclinometers was performed on 18-23.5.2012, after which the measurements are carried out twice a year, usually in late spring and late autumn/early winter period, or after intense rainfalls or strong earthquakes. Until 2015 they were performed with an INTERFELS probe inclinometer, and later with a probe inclinometer developed by ACE INSTRUMENT. However, there are no other measurements related to them, e.g. inclinometer casing top is not surveyed.

2.2 Geodetic surveying

From 2015 to 2017, pre-defined and stabilized geodetic measurement points were set for performing geodetic deformation surveying. Location of geodetic points has been chosen in accordance with the standards for monitoring this type of structures, i.e., points that compose a micro-triangulation network (MTN) and represent a geodetic basis for determining horizontal deformations, elevation network points that represent a geodetic basis for determining vertical deformations and control points in the body of the dam to separate the horizontal and vertical deformations of the structure. Thus, 5 points were set to establish the MTN (B_1, B_2, B_6, B_7 and B_8), 39 control points along the body of the dam and 3 reference levelling points.

The size of the tailings dam (crest length: ~900 m, height: 134 m) draws attention to this structure as the largest one of this type in the country and abroad. These dimensions, the configuration and the afforestation of the downstream slope, limit the possibilities for application of classical geodetic surveying that will result in required accuracy in representing its deformations. To solve this issue, the application of GNSS technology for determination of horizontal deformations and the accurate geometric levelling for determination of the vertical ones are considered as an appropriate choice of geodetic deformation methods that result in sufficient accuracy.

GNSS measurements for determining the horizontal deformations on the dam surface have been carried out since October 2016 in two series per year. The measurements are performed in line with a strictly defined measurement procedure and application of dual-frequency GNSS receivers. Two Trimble R6 receivers, two SOUTH S82T receivers and one Leica GS08 plus and Leica GS 09 receivers were used. All devices share a measurement accuracy of base vectors of 3 mm + 0.5 ppm.

The surveying is carried out with application of GNSS receivers at the same MTN points (Figure 2), i.e., the control points along the dam body in each series of measurements, thus eliminating any possible error due to differences in the phase centres of GNSS antennas of the receivers. The surveying is performed according to the static method with relative positioning based on simultaneous surveying of every single MTN point. Static method of positioning with 15-minute observations is performed for each point along the dam body as well.

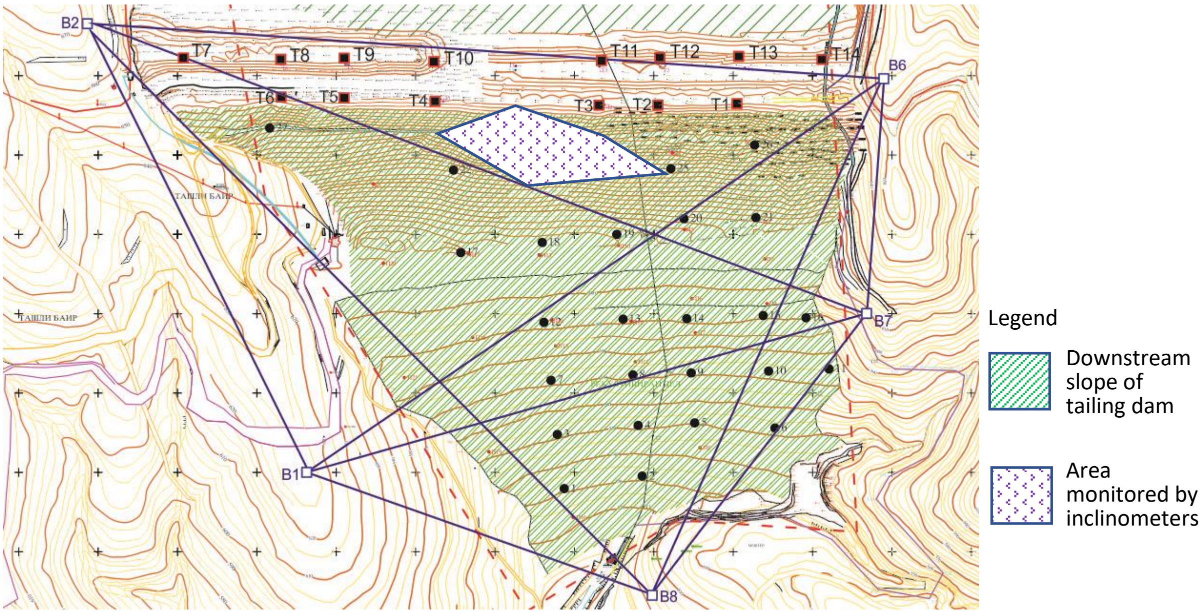

Figure 2: Layout of micro-triangulation and control points networks.

The GNSS positioning in all series of measurements is used to determine the coordinates of the MTN points and the control points network along the body of the dam in the World Geodetic System (WGS 84). Thus, the base vectors of the measurements were adjusted first, and then - based on transformation parameters that were particularly prepared for this area - the coordinates from the World Geodetic Datum were transformed into the State Coordinate System.

Due to a rather low accuracy of the GNSS positioning in determining the vertical components of deformations compared to the horizontal ones, the geodetic deformation surveying of the dam within the TD "Topolnica" is carried out using the method of precise geometric levelling based on the closed polygons rule. For that purpose, during the zero geodetic auscultation in October 2016, the elevation network of the dam was established. It consists of 3 reference (basic) benchmarks near the dam, 2 MTN points and 39 points along the body of the dam.

The levelling procedure in the elevation network for all series of measurements is performed using the precise levelling device Leica DNA03 and accurate barcode invar levelling rods. The declared accuracy of the device is 0.3 mm/km, which fully meets the standards for application in this type of geodetic surveying.

The levelling of the elevation network is performed by indirect measurements, with the average error per unit weight as a parameter of accuracy, ranging from 0.29 - 0.42 mm/km between the series of measurements.

3. Monitoring Results

The results of the decades-long monitoring of TD "Topolnica" are presented in regular monthly, biannual and annual reports submitted to the Mine operator. This paper compares the geodetic and geotechnical measurements carried out between 2016 and 2021, with reference to the displacement of the top of the inclinometer casing.

3.1 Inclinometers

Figure 3 shows the diagrams of cumulative displacements of inclinometers J1 and J2 in direction A (along slope) and in direction B (perpendicular to slope).

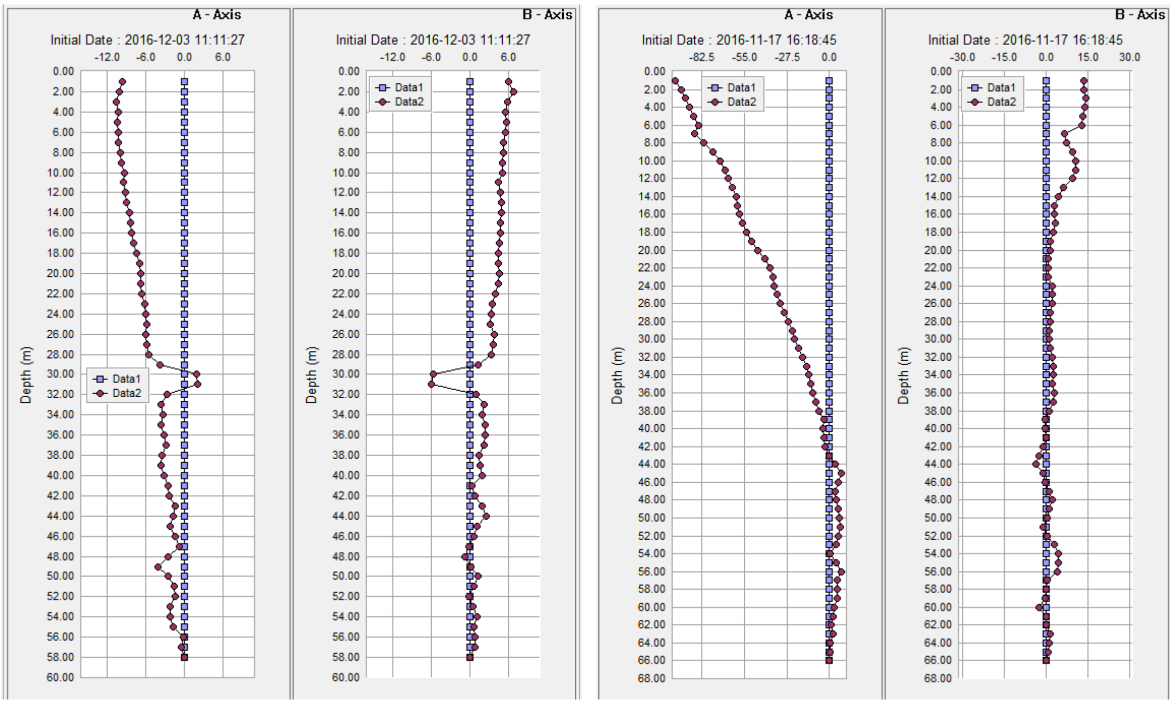

Figure 3: Cumulative displacements of inclinometers J1 (left) and J2 (right) in period 2016-2021.

In the period under review, displacements up to 11 mm in direction A and 7 mm in direction B were registered at the top of the inclinometer casing J1. Thereby, those in direction A are oriented towards north, i.e. towards the tailing dam. At the bottom half of the inclinometer (below 30 m), the displacements are relatively smaller. The discontinuity at 30-31 m might be due to technical installation error, as the casing at this depth is translating parallel to displacements at other depths.

The tendency of displacements in the inclinometer J2 is almost consistent over the years, with displacements in direction A being dominant and amounting to 100 mm in 5 years (towards north), while not exceeding 14 mm in direction B at the top of the inclinometer casing. As it can be noted, the deformations decrease with depth and below 40 m are almost zero.

Figure 4 represents diagrams for inclinometers J3, J4 and J5.

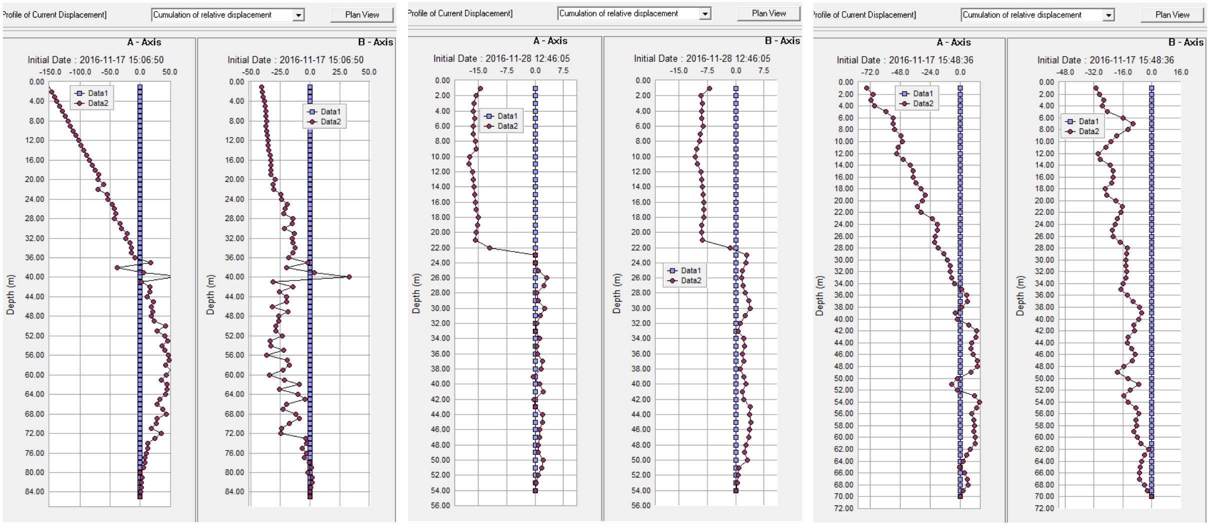

Figure 4: Cumulative displacements of inclinometers J3 (left), J4 (middle) and J5 (right) in period 2016-2021.

The inclinometer J3 is distinct due to its location in a section where the tailing dam reaches its highest point. It is also the deepest one and placed at the highest position. Moreover, just before the application of the brand-new and sophisticated equipment for measuring inclinometers, it was raised for another 6 m in 2015, which caused its bending to some extent and thus making it difficult to establish a direct correlation with the previous measurements. Over the years it has experienced deformations in direction A, which grow slightly in both directions (downstream and upstream) almost along its entire depth, so in the upper 2/3 they are directed upstream, while the lower third is bent downstream. Thus, from 2016 to 2021, a total displacement of 151 mm towards north is produced at the top. Due to high levels of deformation and appearance of the shear in the zone from 36 to 40 m, and thus the expected interruption in further measurements, it was recommended to install a new casing near it, which was done in the second half of 2021. The total displacement at the top of inclinometer in direction B is 41 mm.

The shape of deformations and the depths in which slightly higher displacements occur in the inclinometer J4 are similar to those of J1, which is expected because they are positioned at similar elevations and penetrating the old tailing dam. Regarding the measurement in 2016, the top of the inclinometer has moved 15 mm upstream in direction A (towards north) and 7 mm in direction B. The curve shape indicates that there is a shear zone between 22-23 m depth, which is – respecting the elevation – comparable to the one registered with J1.

The displacements at the top of the inclinometer J5 in the period 2016-21 in direction A are 75 mm, and 31 mm in direction B. As was the case with the other casings, the total displacements are directed upstream.

The excerpt from the summary reviews of displacements during the period 2016-2021 is shown in Table 2.

Label	**Inclinometer tip elevation**	**Length**	**Increase of displacements at the top of the inclinometer casing in the period 2016-21 [mm]**		
	[MASL]	[m]	Direction A (to north)	Direction B	Total
J1	630.73	58	11	7	13
J2	643.76	66	100	14	101
J3	653.00	85	151	41	156
J4	625.00	54	15	7	16
J5	642.94	70	75	31	81

Table 2: Review of observed displacements of inclinometers in period 2016-2021.

3.2 Geodetic surveying

The horizontal and vertical deformations of control points along the dam body are obtained by comparing the results of the recent and previous series of measurements. It should be emphasized that the horizontal geodetic datum of the points is defined through the rectangular coordinates of the micro-triangulation point B_2, and its altitude is used in defining the elevation network datum.

As already emphasized, nine series of geodetic deformation surveying were performed on the dam so far. This paper includes some of the results from the latest series of measurements (2021) and measurements from zero reading (2016).

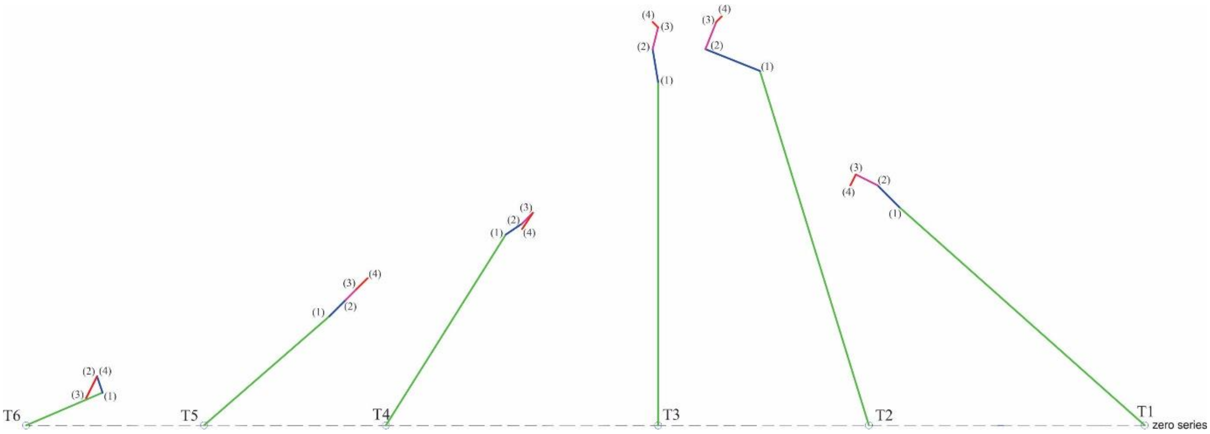

Figure 5: Graphic interpretation of horizontal displacements from series (0) to series (4) for points T1-T6.

The maximum horizontal displacements in relation to the zero series occur at the measuring points of the dam crest. Maximum displacements of 81 mm is registered at point T_{12}, while displacements greater than 40 mm are measured at points T_1, T_2, T_3, T_4, T_5, T_{10}, T_{11}, T_{13} and T_{14}. The inclinometers are placed near the points T_2, T_3 and T_4, so only their values are shown here: T_2=80 mm, T_3=74 mm and T_4=44 mm. However, the direction of the linear deformations at the points of the dam crest and the first bench is perpendicular to the dam crest with direction to the north, i.e., towards the accumulation.

The maximum vertical displacements of the tailing dam surface with respect to the zero series of measurements are also recorded at measuring points of the dam crest: the maximum settlement of -159 mm is at point T_{11}.

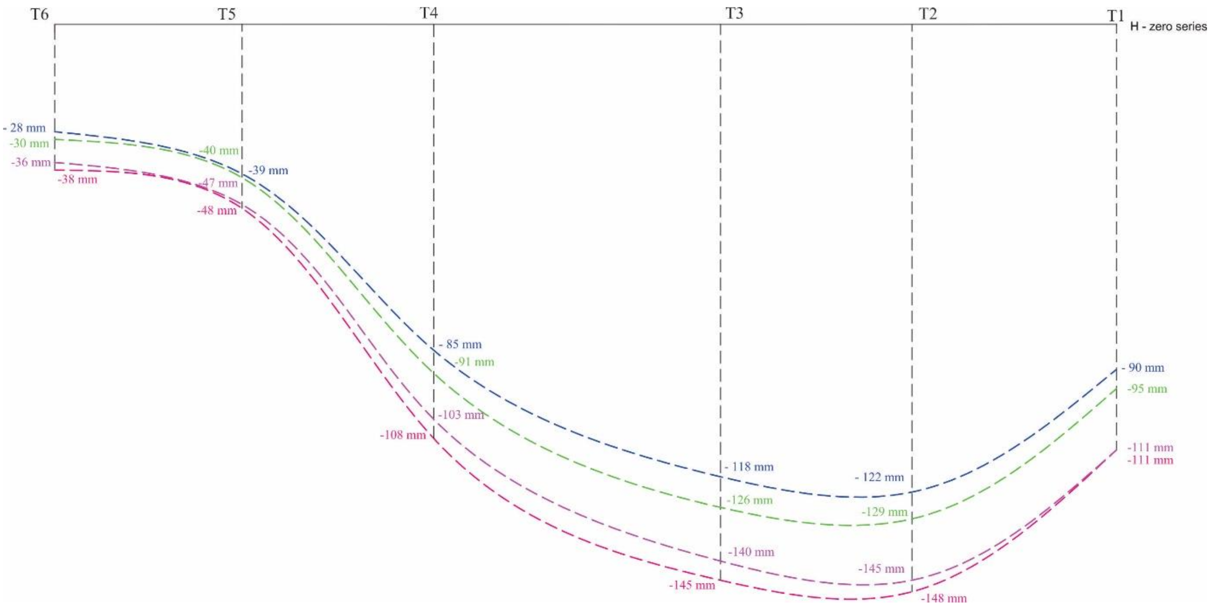

Figure 6: Graphic interpretation of vertical displacements from series (0) to series (4) for points T1-T6.

4. Discussion and Conclusions

Based on the measurements of displacements of the inclinometers, as well as the analysis of presented results, it can be concluded that the inclinometer measurements mostly show displacements. It is noteworthy that casings are displaced upstream for most of their lengths, i.e., towards the tailings dam and to north, which would suggest certain settlement of the fresh material that was deposited in the TD during its latest increase in height. In the period 2016-2021, on the ground surface - at points J1 and J4, displacements were observed in the amounts of 13 mm and 16 mm, respectively, and 81 mm and 101 mm at inclinometers J2 and J5. The maximum displacement of 156 mm was registered for J3. It is evident that no larger displacements were observed at greatest depths, which suggests that the material in the zones that were already filled with tailings (and where the deepest parts of the casings are located) is quite stabilized and strengthened.

The geodetic deformation surveying carried out in the same period suggests that the selected methods for determining the horizontal and vertical displacements along the dam surface meet the standards and required accuracy for this type of facilities. The maximum horizontal displacements occur at the measuring points of the dam crest, while the values of points around the inclinometers are T_2=80 mm, T_3=74 mm and T_4=44 mm. The direction of linear deformations is with direction towards north and accumulation basin.

Having in mind the data obtained during the 2016-2021 surveying, the following can be stated regarding the displacements at the top of the inclinometer casings observed by application of geotechnical methods and the displacements in their nearby surrounding measured by geodetic observations:

- The inclinometer J-1 is located far below the geodetic point T_2, and the registered displacements are 13 mm and 80 mm, respectively;
- J-2 is placed below the point T_3, and the measured displacements are 101 mm and 74 mm, respectively;
- J-3 is placed between points T_3 and T_4, and their displacements are 156 mm, 74 mm and 44 mm, respectively;
- The inclinometer J-4 is located far below J3, and it has displacements of 16 mm;
- J5 is below T4 (displaced by 44 mm), and displacement of 81 mm at the top of the casing was measured.
- J1 and J4 show displacements zone at similar elevation.

Some differences in observed displacements in the considered five-year period are due to the excessive distance between geodetic and geotechnical measuring points, which makes it impossible to establish a strong relation and consistency between the findings. However, it should be noted that all recorded displacements are directed upstream, i.e. towards north and the accumulation basin, regardless of the methods considered and applied.

The surrounding conditions also have some impact. For example, inclinometers J-1 and J-4 are placed in a zone above the initial tailings dam, characterized by compacted material, and are located in a forested part of the slope, due to which deformations are smaller than those of the geodetic surveying. A certain curvature in the displacement diagrams towards zero position in their upper parts could be possibly due to the positive impact of the vegetative root system on the slope stability.

Given the clear correlation of directions (towards north) and similarity of range of displacement values of the ground surface according to different methods and covering a large area, it is recommended to continue with the existing dynamics of observations and to extend to other monitoring methods that will provide regular confirmation of the stability of the largest tailings dam in Macedonia, which is already located and upgraded in rather specific settings.

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