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ASSESSMENT OF REGULAR BEHAVIOR AND STABILITY OF TAILINGS DAMS BY COMPARING CALCULATED AND MEASURED DISPLACEMENTS

Ljupcho Petkovski[1], Stevcho Mitovski[2], Frosina Panovska[3]

Summary

The tailings dams, due to the enormous volume of the waste lagoon, are earth-fill structures with highest potential hazard for the surrounding. However, the numerous reports of collapses of the tailings dams in the last three decades, indicate that the procedures and techniques in the design, construction, maintenance and technical monitoring of the embankment dams for water storage were not applied to the tailings dams, with the same carefulness and the proper caution. The comparison of the calculated and measured horizontal and vertical displacements in the tailings dam post-service period is necessary to make the valid conclusion about the regular behavior and for the satisfactory stability of these complex heterogeneous earth-fill structures.

In this paper, the calculated displacements from the numerical model of the static analysis of the hydro tailings dam Topolnica are compared with the measured values from geodetic, as a part of the monitoring process. The combined tailings dam Topolnica of the copper/gold mine Buchim, Radovish, in the east part of RN Macedonia, is formed by downstream (in the first stage, dam No. 1) and upstream (in the second stage with two phases, dams No. 2-1 and No. 2-2) method of construction, with total height from the crest of the highest dam to the downstream toe of the dam of 141.2 m.

Key words: tailings dams, static analysis, technical monitoring

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1. SUBJECT AND PURPOSE OF THE RESEARCH

Tailings dams are complex engineering structures, composed of starter dam, sand dam, waste lagoon, drainage system, water conveyors for taking out of the cleared water and structures for protection of external water [1, 2]. The tailings, on one side, due to the numerous structures from which are composed, should be checked on great number of static loading conditions, similar as in the case of conventional embankment dams [3], and on the other side, due to the large volume of the waste lagoon, they are embankment structures with highest potential hazard for the surrounding [4]. Due to the enormous importance of the tailings dams, one of the technical committees of ICOLD is the ICOLD Committee on Tailings dams and Waste Lagoons that has published 10 Bulletins [5-14]. Due to the long period of construction, the approach in case of conventional dams (for creation of water reservoirs) for confirmation of the safety of hydraulic structures - with full supervision of the construction and testing of the dam with control of the first filling of the reservoir, as well and the assessment of the regular behavior of the dam with constructed parameters, by comparison with monitoring data in most cases is not fully applied at tailings dams. Unfortunately, such main difference between the conventional embankment dams and tailings dams is enforced at solutions with combined construction [15] and by often requirements for heightening [16], by which is increased the deposit space of the tailings. Here should be point out the additional problems at tailings dams, compared with the conventional dams, due to the settlements in the post-service period from dissipation of the pore pressure in the waste lagoon [17] and increased susceptibility on phenomena of liquefaction [18-21].

During construction of the tailings dam or exploitation of the waste lagoon, as well as in certain post-service period of the tailings dam, the technical monitoring of the dam is necessary. The purpose of the dam monitoring is the necessity for permanent insight in its behavior. Only by technical monitoring of the dam can timely be detected eventual mistakes - design or construction. The timely detection of certain disadvantages at dams is of crucial importance, having in consideration the systems - dams with waste lagoons are in the category of man-made systems with highest potential risk for the downstream river valley. The monitoring of the tailings dam includes carried out measurements for displacements, seepage, total stresses, pore pressures and seismic accelerations. By tracking of the response of the tailings dam at action of various loadings is controlled whether particular structural elements of the dam (and the dam in full) are behaving properly. By proper behavior of the dam is behavior of the structure (with adopted composition, geometry and material parameters), that is estimated (foreseen) with the structural (static and dynamic) analysis during the design stage. According to the method of carrying out of the monitoring of the tailings dam we can differ: visual monitoring, geodetic measurements of surface displacements and monitoring with installed instruments. By engineering interpretation of the measured results from the specified control (obligatory) monitoring is provided systematic explanation of the hydraulic and mechanic response of the tailings dams. Most reliable results for the dam's behavior that should correspond with values from other types of monitoring are obtained with application of geodetic methods. For measurement of the surface displacements in specified measuring spots on the dam body at first is created micro-trigonometrical network from spots for instalment of the geodetic instruments. The benchmarks should be on distance from the dam, in order to be avoided influence from the weight of the tailings dam and from the waste lagoon, on easily accessible locations and by visibility towards the measuring spots of at least three benchmarks. Vertical displacements are measured by leveling, and the horizontal displacements are measured trigonometrically, by precision ±10 mm, as standard for embankments dams.

The monitoring of large dams is not purpose for itself (to fulfill requirements from the legislative), but by comparison of the measured values from the monitoring with calculated values by the mathematical models to brought valid conclusion for the safety of the tailings dam. The purpose of the research is to assess the stability of the combined tailings dam, throughout estimation of the proper response in the post-service period of the tailings dam. The assessment for the normal behavior of the dam (upon construction) is carried out by comparison of the measured surface and calculated displacements by appropriate mathematical models. In here below, the specified will be illustrated by data from the comparison of the calculated and measured displacements in the post-service period for the waste lagoon and tailings dam with combined construction method - Topolnica of mine Buchim, Radovis, N. Macedonia.

2. BASIC PARAMETERS OF THE TOPOLNICA TAILINGS DAM

The tailings dam Topolnica of mine Buchim, Radovish, commenced in 1979, is obtained by deposition of the flotation pulp. By method of hydraulic cycloning from the pulp is created downstream sand dam and by overflow from the hydraulic cyclones (and sometimes and non-cycloned tailings) is discharged in the upstream waste lagoon. In such way, in the waste lagoon is done mechanic deposition of the most fine grains and chemical purification of the used reagents, contained in the tailings. In the past period in the tailings dam Topolnica (Fig. 1) is stockpiled tailings in volume above 130×10^6 m^3 and it is stored water of approximately 9×10^6 m^3.

Such tailings dam is characterized by stage construction and combined method of construction, by downstream advancement at first phase and upstream advancement at heightening from second phase, realized in two stages. The construction of the sand dam in initial phase, till elevation of 610.0 masl (I phase), Fig. 2, was constructed in inclined layers, by advancement in downstream direction from the starter dam, by ground elevation 518.5 masl and crest elevation 558.5 masl. Afterwards, the construction of the sand dam till elevation 630.0 masl (II phase, stage), due to the vicinity of village Topolnica to the downstream toe of the dam, was constructed by filling in upstream direction. In terminal phase is adopted crest elevation of the sand dam at 654.0 masl (II phase, stage 2), by advancement in upstream direction. Fig. 3.

Figure 1. Crest with length of 930.0 m, waste lagoon and cultivated downstream slope of tailings dam Topolnica.

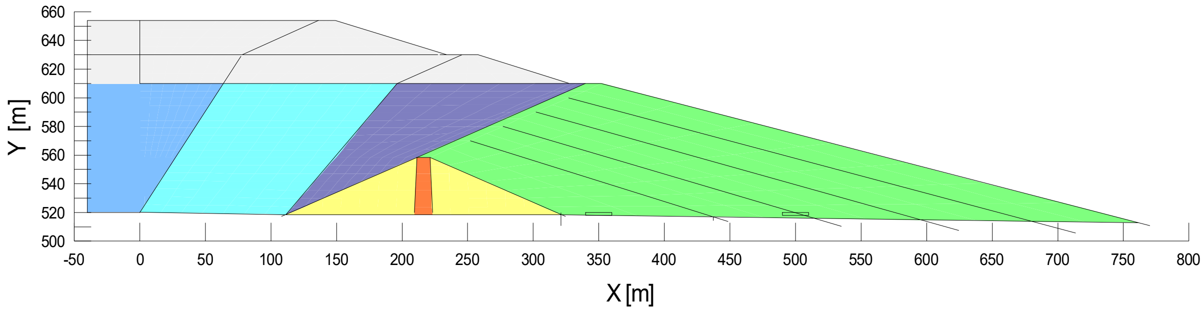

Figure 2. Construction of tailings dam till elevation 610.0 masl (I phase).

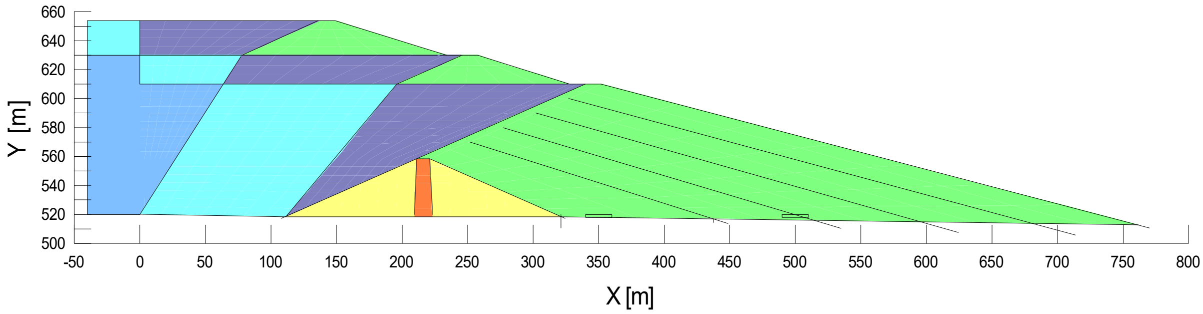

Figure 3. Construction of tailings dam till elevation 654 masl (II phase, stage 2).

The overall dimensions of the representative cross section for structural analysis (static, dynamic and seepage) are width of 801.4 m and height of 141.2 m. The tailings dam Topolnica, by height of dam 2-2 above the ground at started dam of H_0=654.0-518.5=135.5m, is one of the highest tailings dams in Europe. Final height of the tailings dam 2-2, from crest to the downstream toe is H_2=654.0-512.8=141.2 m, by what the tailings dam Topolnica is highest dam in N. Macedonia. Namely, the highest conventional dam (for water reservoir) is dam Kozjak, that according to data for as built drawing, has structural height from dam crest to core foundation of H_c=472.2–341.8=130.4 м. The enormous dimensions of the sand dam, heterogeneous composition of the geo-medium and combined method of construction, downstream in phase I and upstream in phase II, clearly point out that dam Topolnica is one of the most complex and most important embankment structures in N. Macedonia.

3. STATIC ANALYSIS OF THE TOPOLNICA DAM IN THE EXPLOITATION PERIOD

The initial state of stress and development of pore pressure for research of the occurred displacements in the post-service phase of the tailings dam Topolnica is the state immediately after dam construction. The realistic dynamic of the construction of the sand dam is approximated with 48 time steps for the tailings dam, with various time duration. Such 48 time steps are divided on 24 (for started dam and sand dams) and 24 for the waste lagoon, whereas the realistic time for construction of the tailings dam is copied in days (Fig. 4) for the needs of the mathematical model. By the model is simulated the realistic advancement of the tailings dam apropos the filling of the waste lagoon is by appropriate time delay upon construction of the sand dam. The upstream saturation of the tailings, due to the continuous inflow of water from river Topolnica in tailings dam during advancement of the waste lagoon is adopted at 2.0 m lower than the deposited tailings. Such upstream non-steady hydraulic boundary condition is necessary for the analysis of the effective stresses, for alternative with upstream water saturation of the tailings during construction, apropos during service period of the structure.

In such consolidation analysis, by analysis of the effective stresses in drained conditions in realistic time domain [22], is adopted function for filling water in the waste lagoon, as variable upstream boundary hydraulic condition for analysis of the non-steady seepage [24]. In such complex and coupled analysis (by parallel mechanic and hydraulic response) simultaneously are simulated: (a) stage construction, (b) raise and dissipation of the consolidation pore pressure, (c) change of the upstream hydrostatic pressure and (d) heterogeneous medium with irregular geometry. In the analysis, that most realistically copies the behavior of the tailings dam, the material parameters as well and the time component apropos realistic dynamic of construction have the influence.

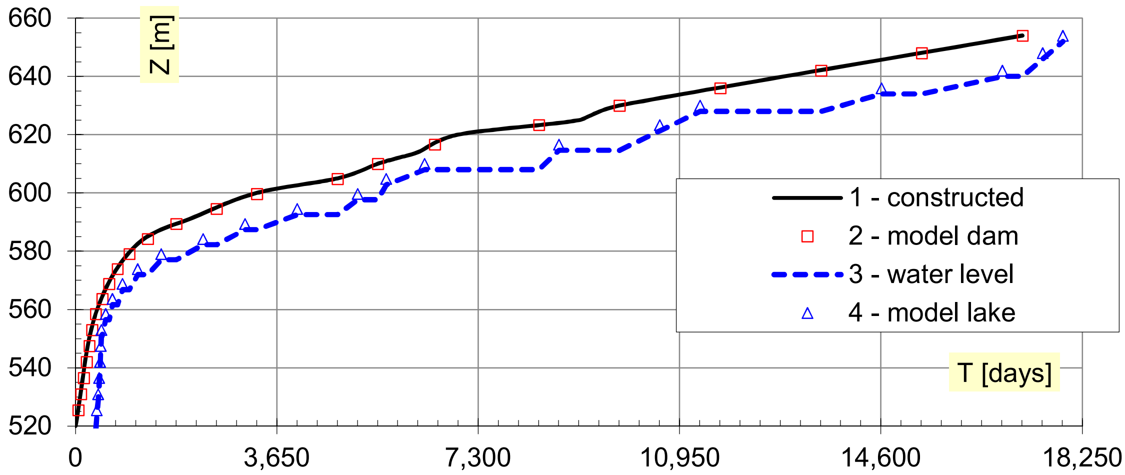

Figure 4. Construction diagram, performed condition in days (1- dam, 3 - lake) and modeled in 48 loading increments with different duration (2 - dam, 4 - lake)

In her below, for construction of dam 2-2 (crest elevation 654.0 masl) are displayed: lines of equal horizontal displacements (Fig. 5), obtained with linear-elastic model, by analysis of the effective stresses in drained conditions and by upstream water saturation. Throughout comparison of the partial displacements in the zone of inclinometer J4 (installed from elevation 625.0 to 570.0 masl), for initial state of construction of dam 2-2 till elevation 630.0 masl and final stage of filling of tailings dam till elevation 654.0 masl, it has been confirmed the proper behavior of the embankment structure and the parameters of the local materials, by which is carried out the static analysis, are verified.

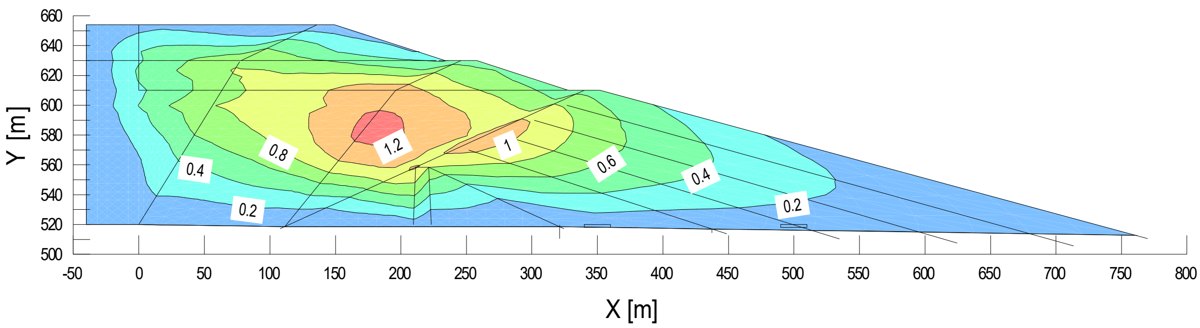

Figure 5. Horizontal displacements in tailings dam, II phase - stage 2 (increment 48), K_{II2}=654.0 masl, X = (-0.000 ÷ 1.249) m

4. ASSESSMENT OF THE BEHAVIOR OF THE DAM TOPOLNICA IN THE POST-EXPLOITATION PERIOD

Within the research of the behavior of the tailings dam, of special interest for determination of the structure's safety is the estimation of the maximal values of the horizontal and vertical displacements of the sand dam in the post-service stage. Such data are important, as for comparison with values from monitoring process (that will be carried out in that period) and for making of valid conclusions for the proper behavior of the tailings dam, as well and for adopting of the required heightening above crest elevation of dam 2-2 at elevation 654.0 masl, by what will be covered residual settlements after dam construction. In research of the response of the tailings dam by elastic-plastic model at transformation of the consolidation pore pressure, generated in final time step in drained conditions, during construction (Fig. 6), in the future post-service period, three scenarios are considered: (1) full dissipation of the consolidation pressure, (2) transformation of the consolidation pressure in steady pore pressure for seepage with constant level of upper water at elevation 630.0 masl (Fig. 7) and (3) transformation of the consolidation pressure in steady pore pressure for seepage with constant level of upper water at 652.0 masl (Fig. 8).

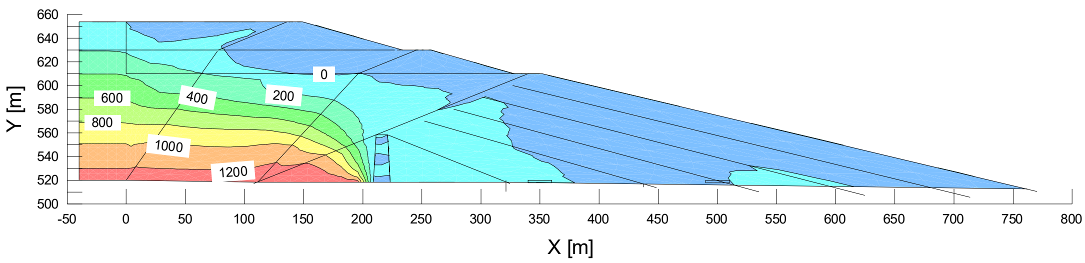

Figure 6. Pore pressure in tailings dam II phase - stage 2 (increment 48) with linear-elastic model, by analysis of effective stresses in drained conditions and upstream water saturation according to the realistic construction dynamic till crest elevation K_{II2}=654.0mnv, P_w=(-157.03÷1309.24) kN/m^2

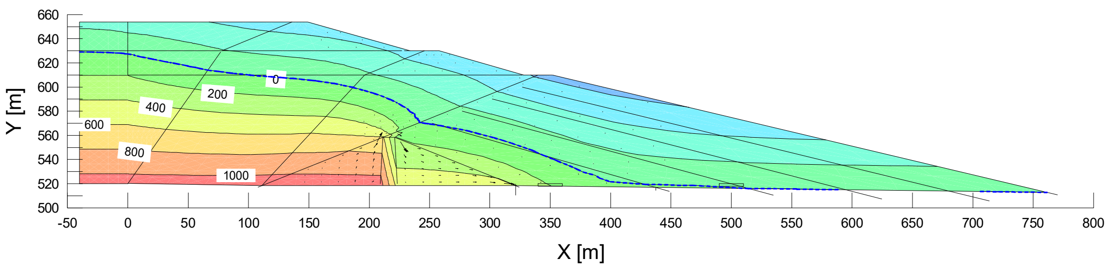

Figure 7. Pore pressure in tailings dam II phase - stage 2, for steady seepage, with upstream water saturation at 630.0 masl, P_w<1093.48 kN/m^2

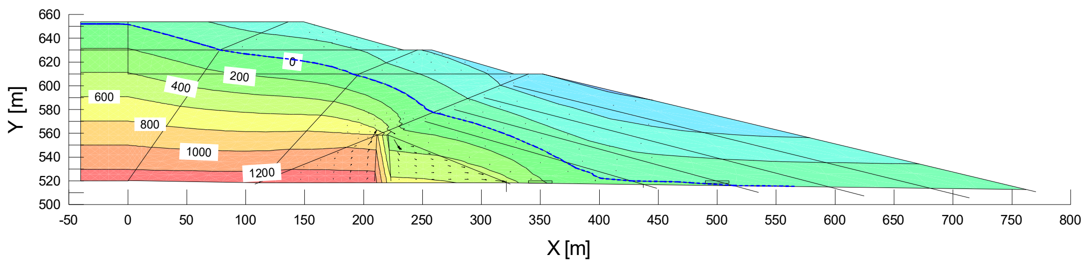

Figure 8. Pore pressure in tailings dam II phase - stage 2, for steady seepage, with upstream water saturation at 652.0 masl, P_w < 1309.23 kN/m^2

The first scenario, by full dissipation of the consolidation pressure (Fig. 9), undoubtedly is fictitious state, because in the post-service period the continuous inflow of water from river Topolnica in the waste lagoon will create steady seepage flow through the tailings dam and most probably will not allow full dissipation of the pore pressure. Therefore, the values from such analysis should be treated as maximal theoretical values. If during the monitoring of the displacements of the sand dam are registered higher values that the specified within the analysis, it is clear indication that there are certain disorder in the proper behavior of the tailings dam.

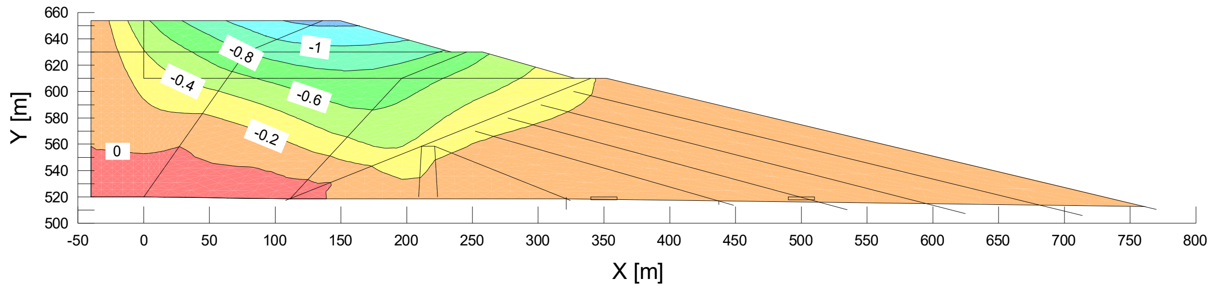

Figure 9. Lines of equal horizontal displacements ΔX=(-1.269) - (+0.057) m, by full dissipation of the consolidation pressure

In case of the second scenario, by transformation of the consolidation pressure in steady pressure for elevation 630.0 masl (Fig. 10), for which we are on opinion that is the most probable in the future, at crest of dam 2-2 at elevation of 654.0 masl the expected displacements are approximately 60.0 cm.

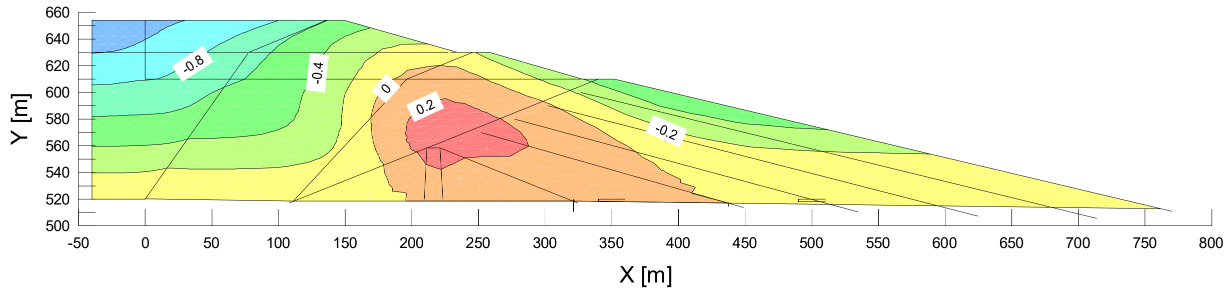

Figure 10. Lines of equal vertical displacements ΔY=(-1.176) - (+0.281) m, by transformation of the consolidation pressure in steady seepage pressure for water at elevation 630.0 masl

For the third scenario, by transformation of the consolidation pressure in steady pressure for elevation 652.0 masl (Fig. 11), for which we are on opinion that it is practically impossible and has theoretic importance as boundary possible state, at crest of dam 2-2 at elevation 654.0 masl, due to the swelling of the material from the upstream water saturation, a raising would occur for approximately 20 cm. However, such value obtained with the elastic response of the embankment structure according to the numerical experiment, in the realistic structure is not possible due to the deformations from creep of the material that is still not possible to be modeled in satisfactory modus.

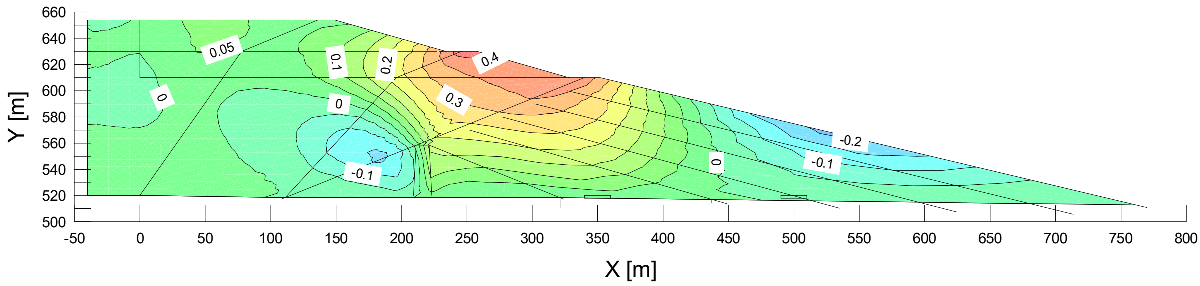

Figure 11. Lines of equal horizontal displacements ΔX = (-0.218) - (+0.431) m, by transformation of the consolidation pressure in steady seepage pressure for water at elevation 652.0 masl.

5. RESULTS FROM THE GEODETIC MEASUREMENTS OF THE DAM TOPOLNICA IN 2019

The geodetic measurements on dam Topolnica, in November 2019, are made on base of the Design for monitoring of tailings dam with appurtenant structures and waste lagoon. The geodetic regards the surface displacements of the measuring spots of the dam, for horizontal (positional) and vertical displacements. The maximal displacements (upstream) are in point T2, value of 6.4 cm and vertical displacement in point T2, value of 10.8 cm. The relevant calculated displacements for comparison with the measured values from technical monitoring are obtained with mathematical model for seepage flow and response of the dam at action of static loadings. By such model for tailings dam 2-2 is estimated the response and stability of the tailings dam, by use of: (a) constructed geometry for the dam, (b) data for behavior of the dam from previous monitoring, for calibration of the material parameters and (c) advanced models for numerical analysis of embankment dams.

By comparison of the measured displacements from geodetic monitoring in November, 2019 (for upstream seepage condition at 641.0 masl and zero state for October, 2016) with the calculated by the mathematical model for static and seepage analysis (for full dissipation of the pore pressure in post-service period, by upstream seepage condition on 630..0 masl, in period immediately after dam construction), we consider that dam of tailings dam Topolnica, Radovish, behaved properly in November, 2019. Namely, the calculated values for the full post-service period for maximal displacements in crest of dam 2-2, at elevation 654.0 masl are horizontal upstream, value of 30 cm and vertical displacement of 50 cm. The measured maximal values (period 10.2016 – 11.2019) are part of the calculated and are with value for horizontal upstream 6.4 cm and vertical displacement (settlement) of 10.8 cm.

The direction of the measured displacements is identical with the calculated and the ratio between the horizontal and the vertical displacements is approximately equal apropos (30/50=0.60) ≈ (6.4/10.8=0.59). According to the intensity of the measured values, it can be concluded that in the period of geodetic monitoring (10.2016-11.2019), 21.6% from the calculated displacements have occurred that regards for the full future period after dam construction. Such three parameters: (a) direction of displacements, (b) ratio between the horizontal and vertical displacements and (c) intensity of the displacements, are key for assessment of the proper behavior of the combined tailings dams and therefore it can be concluded that the tailings dam for the moment is acting by proper response.

According to the intensity and direction of the measured horizontal displacements, greatest values for the upstream displacements at crest of dam 2-2, elevation 654.0 masl (Fig. 12) are slightly lower than the downstream displacements at crest of dam 2-1, elevation 630.0 masl (Fig. 13). The intensity and direction of the calculated horizontal displacements at crest for dams 2-2 and 2-1 is identical, and the ratio of the intensity is similar, that is higher in case of the mathematical model, because it regards on infinite time period, and not for period of 3 years, that has been covered in the geodetic monitoring.

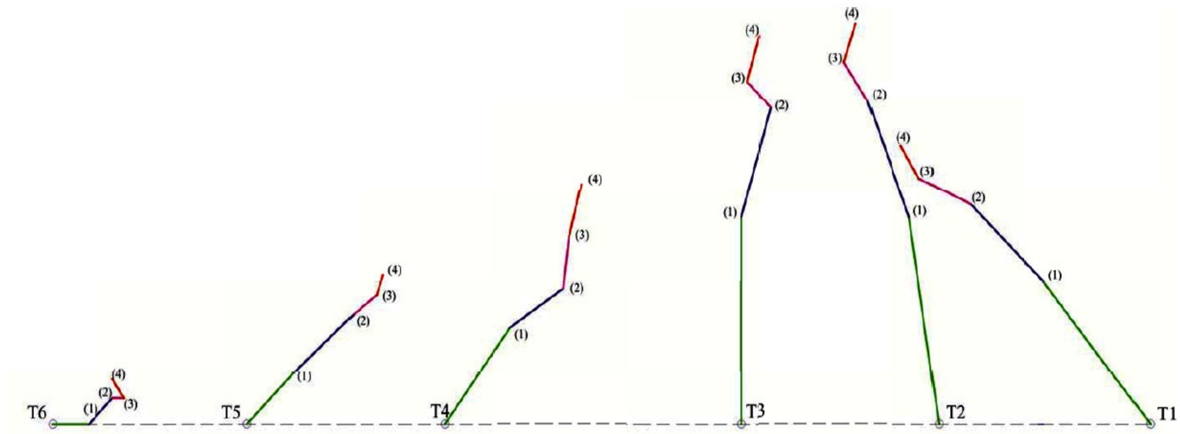

Figure 12. Horizontal displacements at crest of dam 2-2 at elevation 654 masl, from series 0 to series 4

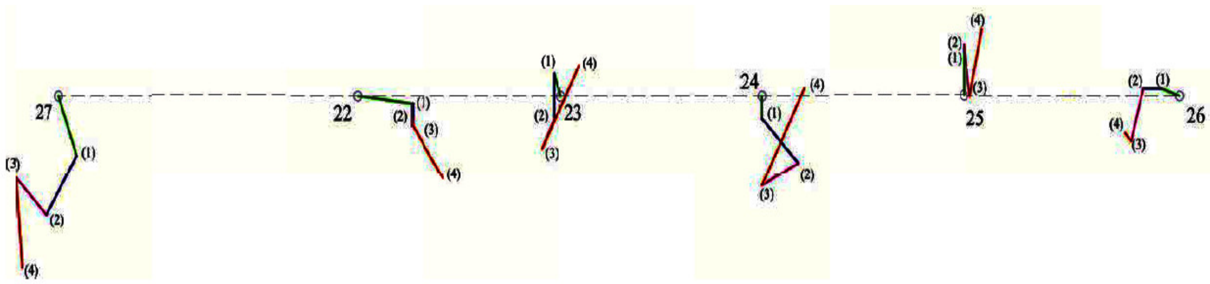

Figure 13. Horizontal displacements at crest of dam 2-1 at elevation 630 masl, from series 0 to series 4

According to the measured vertical displacements, their intensity decreases from 10.8 cm at crest of dam 2-2 (elevation 654 masl), Fig. 14, to 2.3 cm at crest of dam 2-1 (elevation 630 masl), Fig. 15. Similar response is obtained and by the mathematical model, whereas the settlements are decreased from 50 to 10 cm, so that the ratio of decrease is approximately equal apropos (50/10=5.0) ≈ (10.8/2.3=4.7).

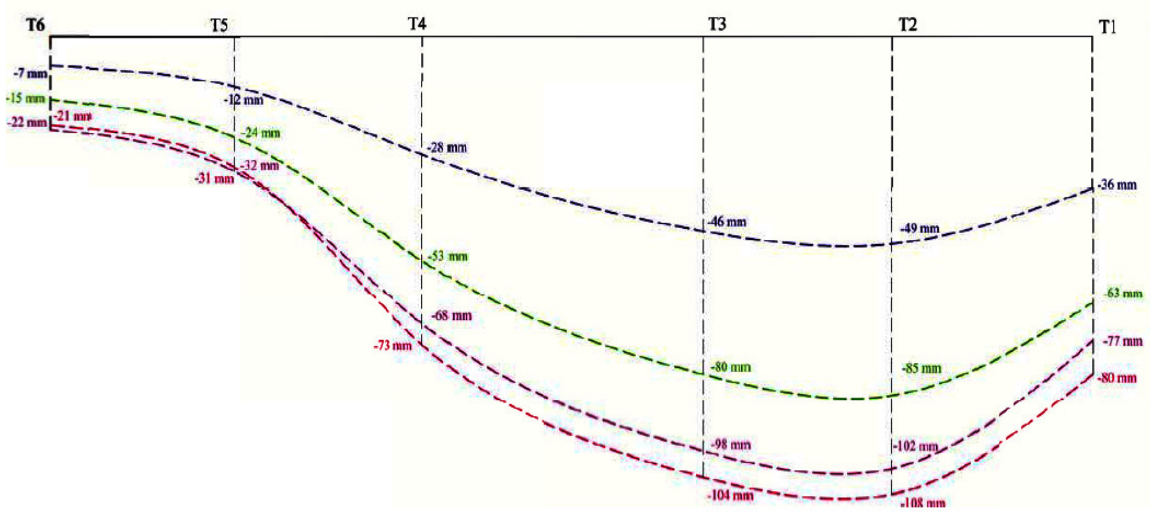

Figure 14. Vertical displacements (settlements) at crest of dam 2-2 at elevation 654 masl, from series 0 to series 4

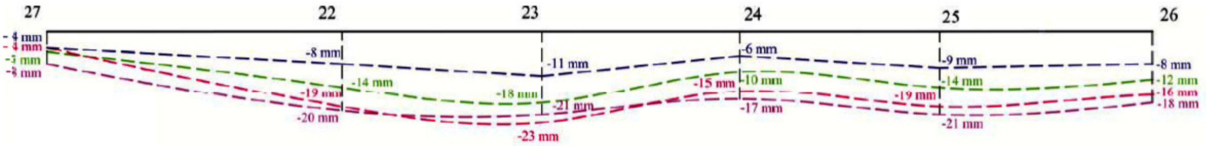

Figure 15. Vertical displacements (settlements) at crest of dam 2-1 at elevation 630 masl, from series 0 to series 4

6. CONCLUSION ON THE RESPONSE AND STABILITY OF THE DAM

The importance of the monitoring measurements (geodetic and instrumental) is to assess the degree of proper behavior of the dam. If there are registered displacements in various direction and by greater intensity from the calculated, then that is an alarm that something irregular is taking place in the embankment structure. In such case should be performed additional geotechnical investigations and to be updated the analysis of the state of stress and deformation, in order to discover the reason and afterwards to carry out restoration of the dam.

By comparison of the measured values for the surface displacements, positional (horizontal) and vertical on the dam body, systemized in the elaborate for geodetic measurements in November, 2019 and calculated displacements in the body of dam Topolnica it can be concluded that measured displacements are in same direction, but with lower intensity from the calculated with the mathematical model. Therefore, we consider that the dam is acting properly in the past period and that by acknowledgments from the interpretation of the geodetic monitoring in November, 2019, it can be concluded that the dam stability is on satisfactory level.

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