NUMERICAL ANALYSIS OF DISPLACEMENTS IN THE POST-EXPLOITATION PERIOD OF TAILINGS DAMS WITH A COMBINED CONSTRUCTION METHOD

AUTHORS

Ljupcho Petkovski
Ph.D. Full Professor
University Ss. Cyril and Methodius
Faculty of Civil Engineering – Skopje
petkovski@gf.ukim.edu.mk

Stevcho Mitovski
Ph.D. Assistant Professor
University Ss. Cyril and Methodius
Faculty of Civil Engineering – Skopje
s.mitovski@gf.ukim.edu.mk

The similarities between the tailings dams and the embankment dams for water storage have contributed a great number of procedures and techniques in the design, construction and maintenance of the conventional dams, to be applied to tailings dams. However, the numerous reports of collapses of the tailings dams in the last three decades, all over the World, indicate that the structural, (static and dynamic), filtration, hydrological and hydraulic safety were not controlled with the same rigor and carefulness - as for the embankment dams. This fact, in part, results from the long-term construction of the tailings dams, where the building material is sand obtained by separating the waste material from the floatation process during the exploitation of the mine. This paper presents the results from the static analysis of the hydro tailings Topolnica, on the river Topolnica, in the east part of Republic of Macedonia. It is a tailings dam with a combination of downstream (in the first phase) and upstream (in the second phase) methods of construction, with a total height from the crest to the downstream toe of the dam of 141.2 m.

Keywords: tailings dams, combined construction method,

1. INTRODUCTION

Tailings dams are complex engineering structures, composed of an initial dam, sand dam, waste lagoon, drainage system, outlet pipe for discharge of clear water, and structures for protection in case of inflow (external) water [Petkovski L., Gocevski B., Mitovski S., 2014.06], [Petkovski L., Peltechki D., Mitovski S., 2014.09].

The tailings, on one hand, due to the numerous structures of which are composed, should be checked on great number of safety cases at static loading, similar as for conventional fill dams [Petkovski L., Tanchev L., Mitovski S., 2007. 06], and on other hand, due to the enormous volume of the waste lagoon, they are fill structures with highest potential hazard for the surrounding [Petkovski L., Mitovski S., 2015.06]. Due to the great importance of the tailings dams, one of the ICOLD's Technical Committees is exactly for tailings dams and deposit lakes - ICOLD Committee on Tailings dams and Waste Lagoons), that has published 1o Bulletins, [ICOLD, 1982, Bulletin 45] - [ICOLD, 2011, Bulletin 139].

Due to the long construction period, the approach for conventional dams (for creation of water reservoirs) for confirmation of proper accomplishment of the hydraulic structures – with full supervision of the construction and control of the first reservoir filling, as well and the assessment of the dam's proper behaviour with construction parameters throughout comparison with monitoring data, at most cases is not applied fully in case of tailings dams. Unfortunately, such main difference between the conventional and tailings dams is amplified in case of technical solutions with combined construction method [Petkovski L., 2015.09] and heightening [Petkovski L., Mitovski S., 2012.10] thus providing increase of the deposit space of the tailings dams. The purpose of the research is to analyse the settlements in tailings dams body upon service period of the waste lagoon to plan the dam crest heightening and to estimate limit value for the displacements, in order to compare with measured values within monitoring process, so the proper conclusion can be drawn out for the regular behavior of the dam in the future period. In the below text, the paper will be illustrated with data from the research of the displacements in the post service period of the waste lagoon, generated with various scenarios for pore pressure dissipation within the tailings, for tailings dam Topolnica of mine Buchim, Republic of Macedonia, with combined construction method.

2. BASIC PARAMETERS OF TAILINGS DAM TOPOLNICA

Tailings dam Topolnica of mine Buchim, Radovish, commissioned in 1979, is created by deposition of the flotation pulp. By the method of pulp hydro-cycling, from the sand is created the downstream sand dam, and the spillway from the hydro-cyclones (sometimes and non-cycled tailings) is released in the upstream waste lagoon. In such way in the waste lagoon is done mechanical deposition of the finest particles and chemical purification of the used reagents, present in the tailings. In the past period in tailings dam Topolnica (fig. 1) is deposited tailings volume over 130 million m^3 and water is stored in volume of approximately 9 million m^3.

Figure 1. Crest and waste lagoon of tailings dam Buchim, March, 2016

The tailings dam is characterized with stage construction and combined construction method, by downstream progressing in first stage and upstream progressing at heightening from second stage, in two phases. The construction started with the initial dam, fig. 2, with foundation elevation 518.5 masl and crest elevation 558.5 masl. The construction of the sand dam in first stage, up to elevation 610 masl (I stage), fig. 3, was constructed in inclined layers, by progressing in downstream direction from the initial dam. Afterwards, the construction of the sand dam to elevation 630 masl (II stage, phase 1), due to the vicinity of village Topolnica to the downstream toe of the dam, was constructed by filling in upstream direction, fig. 4. At terminal stage is adopted sand dam crest at 654.0 masl (II stage, phase 2), by progression in upstream direction, fig. 5.

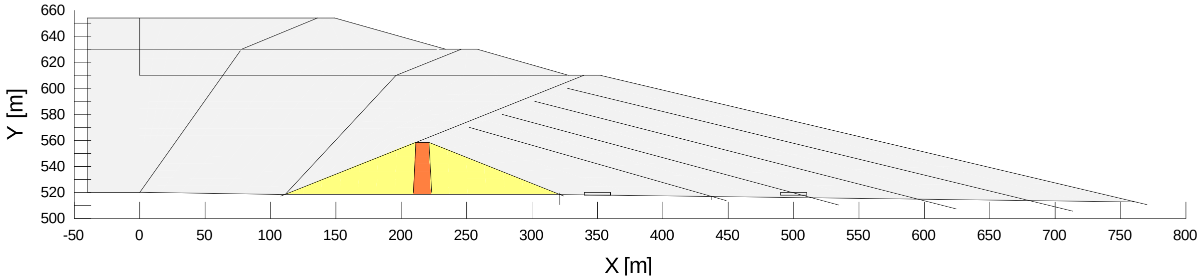

Figure 2. Construction of initial dam to elevation 558.5 masl

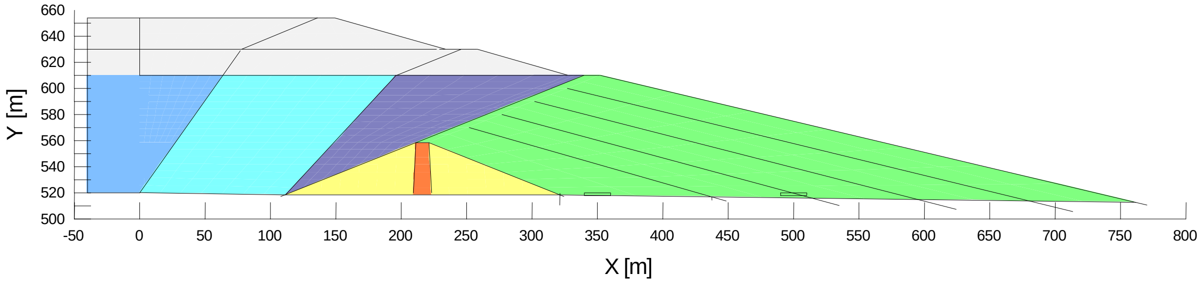

Figure 3. Tailings dam construction to elevation 610 masl (I stage)

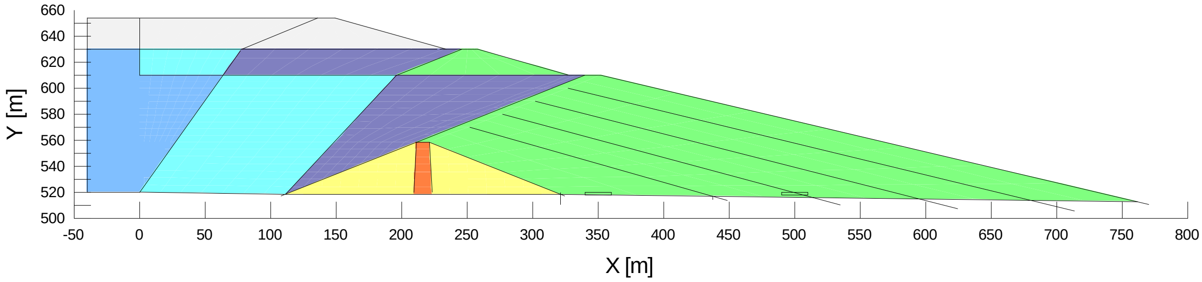

Figure 4. Construction of tailings dam to elevation 630 masl, (II stage, phase 1)

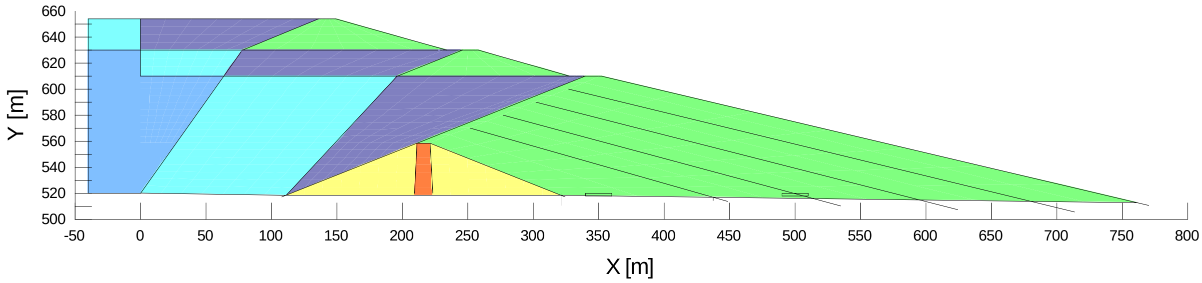

Figure 5. Construction of tailings dam to elevation 654 masl, (II stage, phase 2)

The overall dimensions of the representative cross section for structural (static and dynamic) analysis are: length 801.4 m and height 141.2 m. The tailings dam Topolnica, with height of dam no. 2-2 above the foundation of initial dam of H_0 =654.0-518.5=135.5 m, is one of the highest tailings dams in Europe. The final height of the tailings dam no. 2-2, from crest to downstream toe, is H_2 = 654.0 - 512.8 = 141.2 m, by what Topolnica tailings dam is highest dam in R. Macedonia. Namely, the highest conventional dam (for water reservoir), dam Kozjak, according to as built data from 2001, has height from dam crest to core foundation of 472.2 – 341.8 = 130.4 m. The enormous dimensions of the sand dam, heterogeneous composition of the geo-medium and combined construction method, downstream in stage I and upstream in stage II, obviously shows that dam Topolnica is one of the most complex and most important fill structures in R. Macedonia.

Regarding the geomechanical parameters of the local materials, from which the tailings dam is constructed certain approximations are foreseen, thus contributing to simplification of the numerical experiment, and in same time does not decrease the safety analysis. The simplification of the material parameters is provided by the following approximations: (1) the waste lagoon, possessing highly non-specified and heterogeneous composition, by finer grain size fractions in the upstream and coarser grain size particles in the downstream part of the sand dam, is represented with 3 different materials; (2) the filter transition zones in the initial dam are neglected, for which is estimated that they have small dimensions, compared to the geostatic medium from interest in the analysis. In such a way is prepared idealized cross section for structural analysis, and the heterogeneous composition of the tailings dam is modelled with number of segments by 6 different materials, (fig. 6). The discretization of the tailings dam for static analysis (fig. 7) is done in order to model the stage construction, by development and dissipation of the consolidation pore pressure.

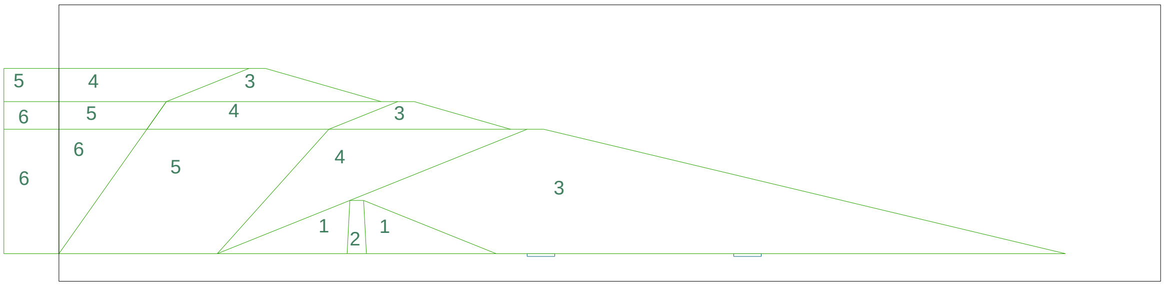

Figure 6. Segments by 6 different materials. 1 – gravel in initial dam body, 2 – clay in initial dam core, 3 – sand in tailings dam, 4 – sand silt in beach, 5 – sand silt between the beach and lagoon and 6 – silt in waste lagoon

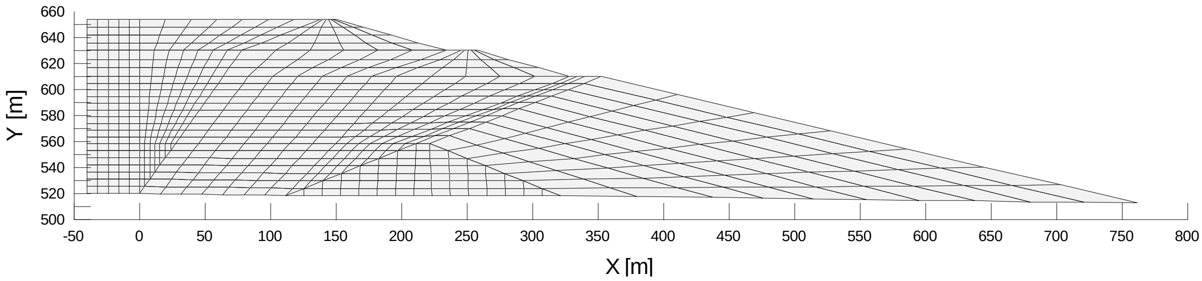

Figure 7. Discretization of the mediums for static analysis by FEM (N=725, E=687)

3. MODELING OF TAILINGS DAM CONSTRUCTION STAGE

The initial state of stresses and development of pore pressure for analysis of the displacements in the post-service stage of tailings dam Topolnica is state of dam construction. The realistic construction dynamics of the sand dam is approximated in 48 time steps for the tailings dam, with different duration. Such 48 time stages are divided on 24 (for initial and sand dams) and 24 for the waste lagoon, whereas the realistic time for tailings dam construction is simulated in days (fig. 8) for the needs of the mathematical model. Realistic progress of the tailings dam is simulated by the model, apropos filling of the waste lagoon is by appropriate time delay upon sand dam construction.

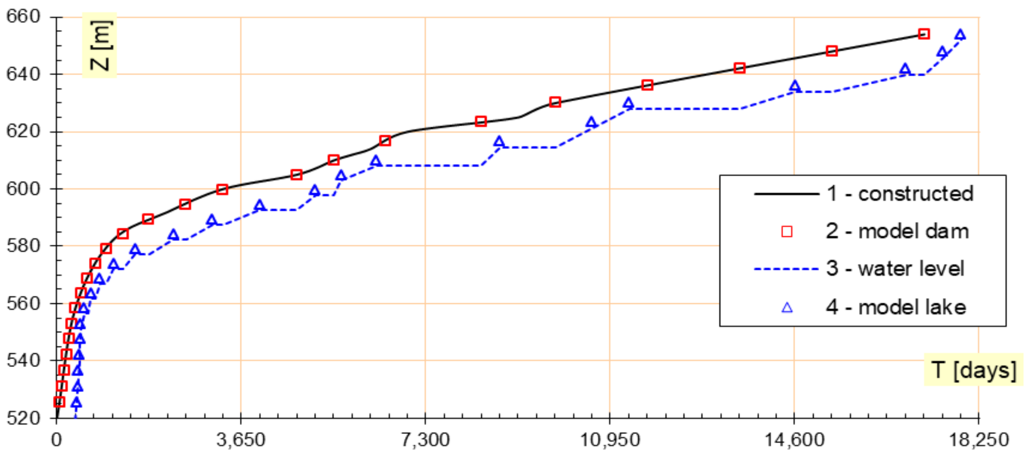

Figure 8. Construction chart, constructed (1 - dam, 3 - lagoon) and modeled (2 - dam, 4 – lagoon) state, in days

The upstream water saturation of the tailings due to the existing water inflow from river Topolnica in the tailings dam during progressing of the waste lagoon is adopted to be 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 the alternative with upstream water saturation of the tailings during construction, apropos for the service period of the structure. In the present consolidation analysis, by analysing the effective stresses in drained conditions in realistic time domain [Geo-Slope SIGMA/W, 2012] is adopted water filling function in the waste lagoon, as variable upstream boundary condition for analysis of the non-steady seepage [Geo-Slope SEEP/W, 2012]. In such complex and coupled analysis (by parallel mechanical and hydraulic response), in the same time are simulated: (a) stage construction, (b) development and dissipation of consolidation pore pressure, (c) change of the upstream hydrostatic pressure and (d) heterogeneous medium by irregular geometry. In the analysis, that simulates the tailings behaviour most realistically, the material parameters have influence and also the time component, apropos the realistic construction dynamics. In continuation, for construction of dam no. 2-2 (for crest elevation 654.0 masl) are displayed: iso-lines of vertical displacements (fig. 9), horizontal displacements (fig. 10) and maximal normal total stresses (fig. 11). Throughout comparison of the partial displacements in zone of the inclinometer J4 (installed from elevation 625 masl to 570 masl), for initial state for construction of dam no. 2-2 up to elevation 630 masl) and final state for filling of the tailings till elevation 654 masl, it has been verified the regular behaviour of the embankment structure and also are verified the material parameters for the local materials adopted for the static analysis.

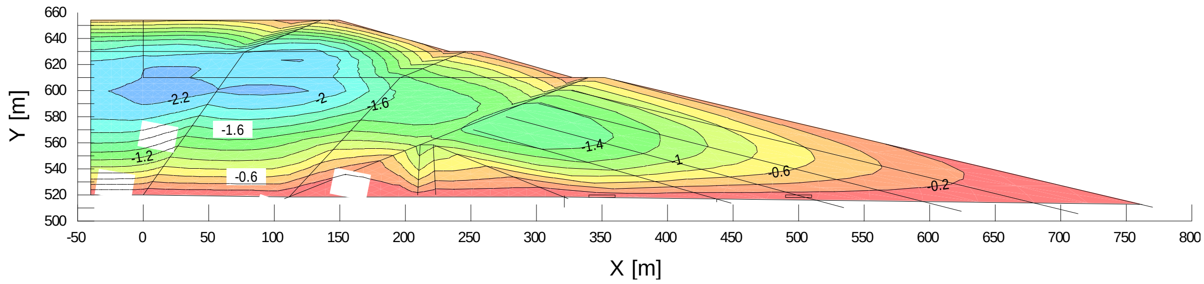

Figure 9. Vertical displacement in tailings II stage - phase 2 (increment 48), by linear-elastic model, by analysis of the effective stresses in drained conditions with upstream water saturation, K_{II2} = 654.0 masl, Y=(-2.347÷ 0.000)m

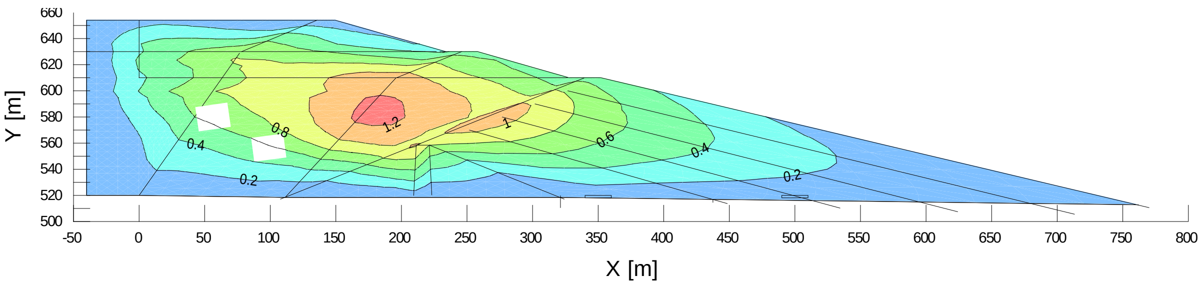

Figure 10. Horizontal displacement in tailings II stage - phase 2 (increment 48), by linear-elastic model, by analysis of the effective stresses in drained conditions with upstream water saturation, K_{II2} = 654.0 masl, X = (-0.000 ÷ 1.249) m

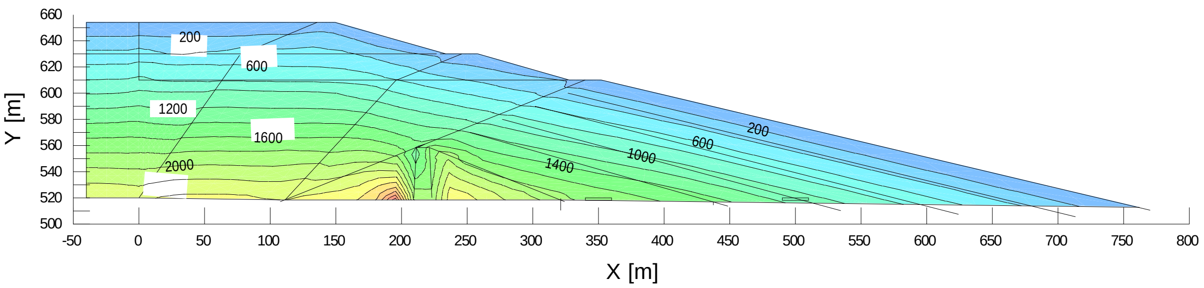

Figure 11. Maximal normal total stresses in tailings II stage - phase 2 (increment 48), by linear-elastic model, by analysis of the effective stresses in drained conditions with upstream water saturation, K_{II2} = 654.0 masl, σ_1 = (25.19 ÷ 3503.14) kN/m^2

4. MODELING OF POST- EXPLOITATION STATE

Within the research of the behavior of the tailings dam, of special interest for the finding of the structure safety is the assessment of the maximal values of the horizontal and vertical displacement of the sand dam in the post-service stage. Such data are important, for comparison with monitoring data (the monitoring process will take place during service period) as well for making valid conclusions for the proper behavior of the tailings dam and as for adoption of required heightening above crest of dam no. 2-2 at elevation 654.0 masl, that will include the residual settlements after dam construction. In the research of the tailings dam response by elastic-plastic model at transformation of the consolidation pore pressure, generated in the final time step in drained conditions, during construction (fig. 12), in the future post-service period are analyzed three scenarios: (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 630.0 masl (fig. 13) and (3) transformation of the consolidation pressure in steady pore pressure for seepage with constant level of upper water at 652.0 masl (fig. 14).

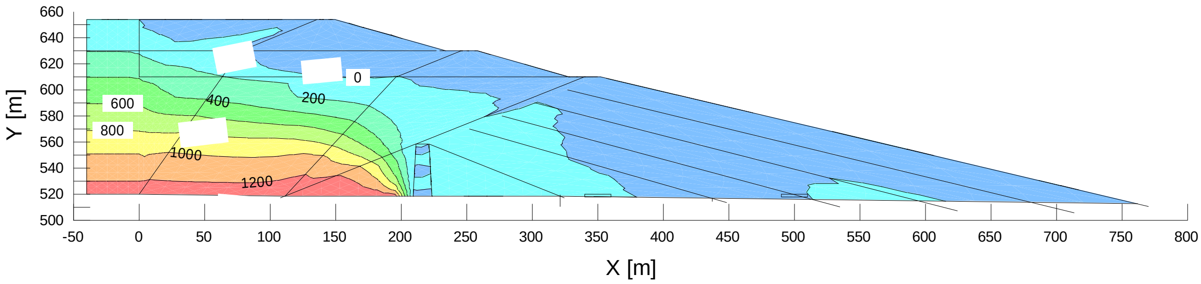

Figure 12. Pore pressure in tailings dam II stage - phase 2 (increment 48), by linear-elastic model, analysis by effective stresses in drained conditions with upstream water saturation according to the realistic construction dynamics up to crest elevation K_{II2} = 654.0 masl, P_w = (-157.03 ÷ 1309.24) kN/m^2

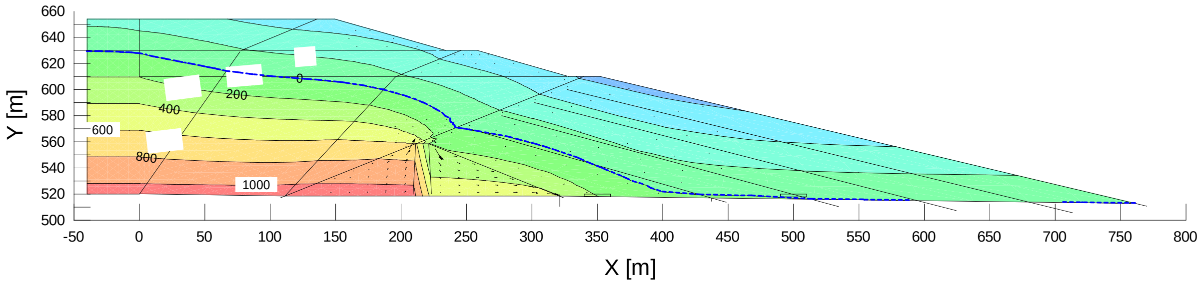

Figure 13. Pore pressure in tailings dam II stage - phase 2 for steady seepage, with upstream water saturation at 630.0 masl, P_w < 1093.48 kN/m^2

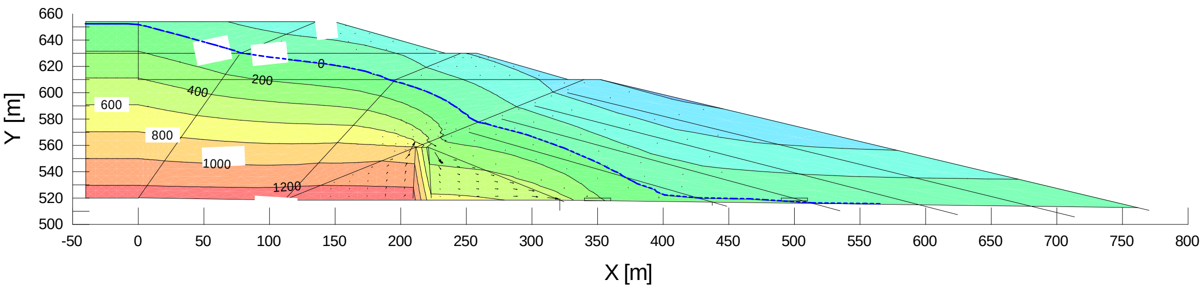

Figure 14. Pore pressure in tailings dam II stage - phase 2 for steady seepage, with upstream water saturation at 652.0 masl, P_w < 1309.23 kN/m^2

RESULTS FROM ANALYSIS OF THE POST-SERVICE STATE

The first scenario, by full dissipation of the consolidation pressure (fig. 15 and 16) undoubtedly is fictive state, because in the post-service period, the existing inflow of water from river Topolnica in the waste lagoon will create steady seepage regime through the tailings dam, and most probably will not allow full dissipation of the pore pressure. Therefore, the value of such analysis should be treated as maximal theoretical values. If during displacements monitoring for the sand dam are recorded values higher that the specified in the analysis, that is certain clue that there are some anomalies in the regular behavior of the tailings dam.

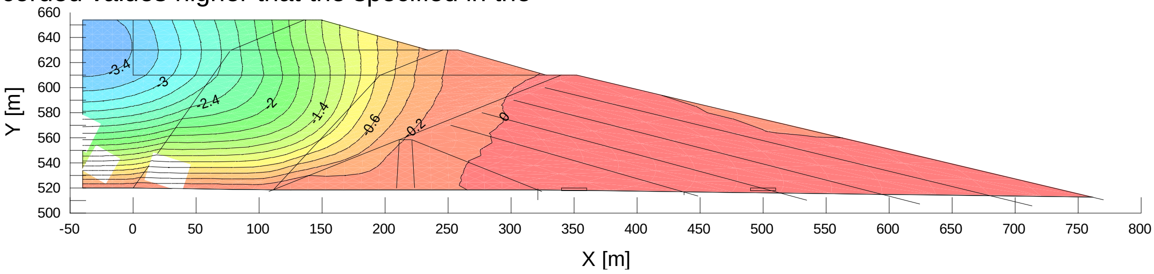

Figure 15. Isolines of vertical displacements ΔY = (-3.583) - (+0.023) m, by full dissipation of the consolidation pressure

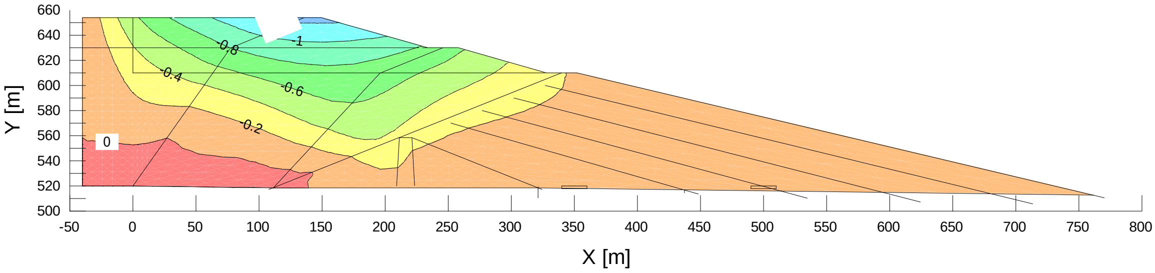

Figure 16. Isolines of horizontal displacements ΔX = (-1.269) - (+0.057) m, by full dissipation of the consolidation pressure

For the second scenario by transformation of the consolidation pressure in steady regime at elevation 630.0 masl (fig. 17 and 18), for which we are on opinion that is it most probable for the future period, in the crest of dam no. 2-2 at elevation 654.0 masl the expected settlements are approximately 60.0 cm.

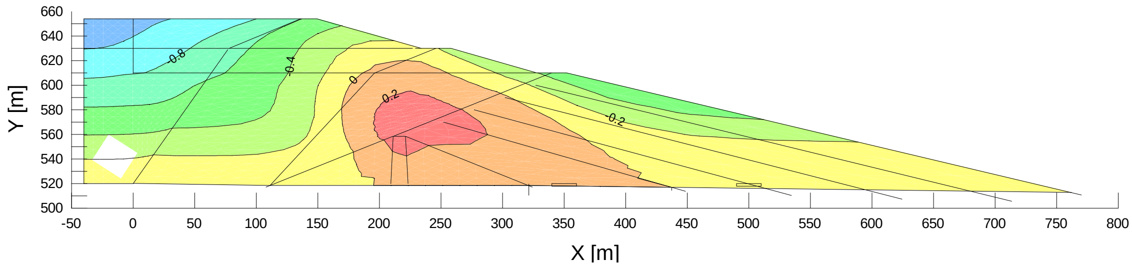

Figure 17. Isolines of vertical displacements ΔY = (-1.176) - (+0.281) m, by transformation of the consolidation pressure, in steady seepage pressure at upper water elevation 630.0 masl

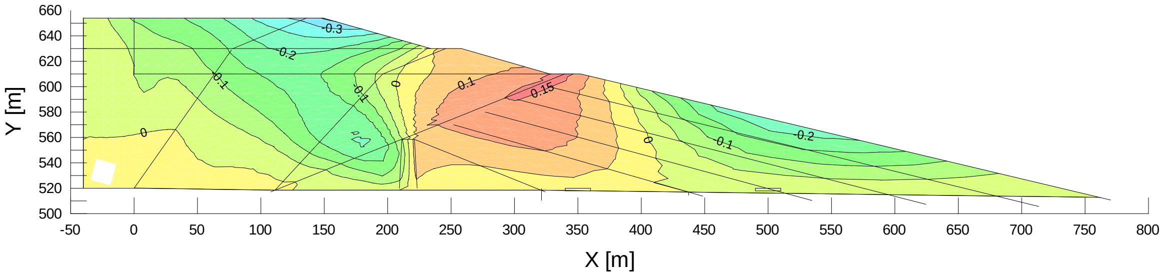

Figure 18. Isolines of horizontal displacements ΔX = (-0.363) - (+0.177) m, by transformation of the consolidation pressure, in steady seepage pressure at upper water elevation 630.0 masl

For the third scenario by transformation of the consolidation pressure in steady pressure at elevation 652.0 masl (fig. 19 and 20), for what we think that is practically impossible and it serves as theoretical knowledge as possible boundary state, in crest of dam no. 2-2 at elevation 654.0 masl, due to the material swelling from the upstream water saturation, there is occurrence of rising of approximately 20.0 cm. But, such value obtained by elastic response of the fill structure according to the numerical experiment, in the realistic structure it is not possible due to the deformations caused by creep of the material, that cannot be modeled yet in satisfactory way.

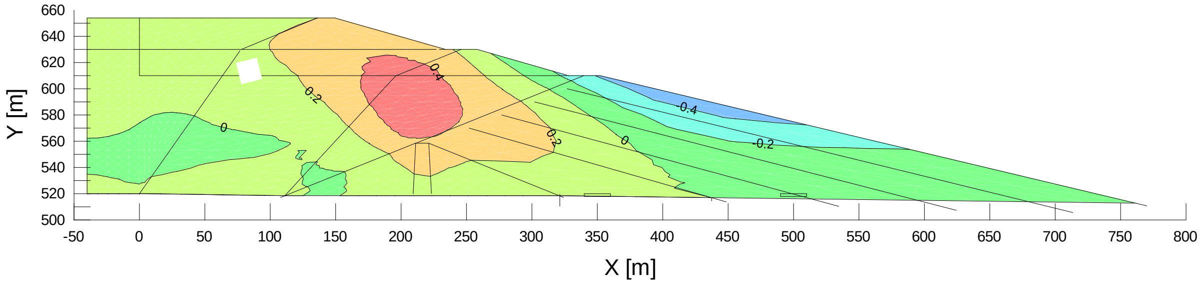

Figure 19. Isolines of vertical displacements ΔY = (-0.553) - (+0.497) m, by transformation of the consolidation pressure, in steady seepage pressure for upper water at 652.0 masl

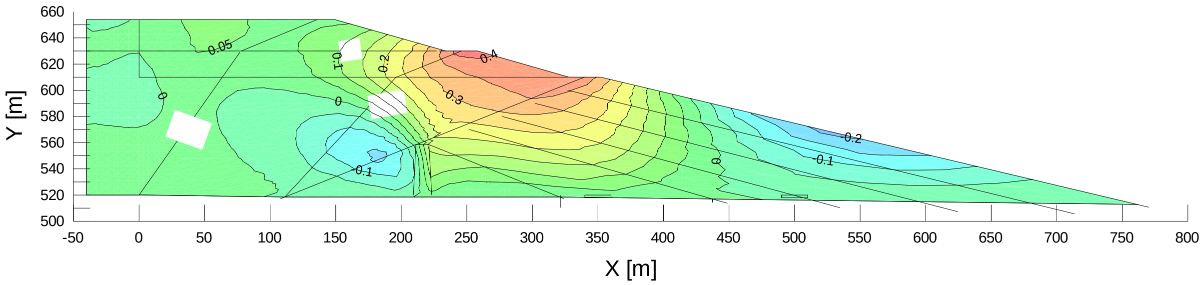

Figure 20. Isolines of horizontal displacements ΔX = (-0.218) - (+0.431) m, by transformation of the consolidation pressure, in steady seepage pressure for upper water at 652.0 masl

CONCLUSION

For assessment of the maximal value of the horizontal and vertical displacement in the sand dam post-service stage, three scenarios are analyzed for transformation of the consolidation pore pressure generated in the final time step in drained conditions during construction.

The first scenario is by full dissipation of the consolidation pressure apropos full dry out of the waste lagoon that is practically impossible due to the natural inflow of river Topolnica. This is the most pessimistic scenario and the values for crest settlements of dam no. 2-2 at elevation 654.0 masl, obtained approximately 140-160 cm, and should be treated as maximal theoretical values. If during monitoring of the displacements of the sand dam are registered higher values then the specified that is sure clue that there are some anomalies in the regular behavior of the dam apropos occurrence of not-permitted seepage, followed by process of mechanical suffusion that can cause collapse of the fill structure.

The second scenario is by transformation of the consolidation pressure in steady pore pressure for seepage at constant level of upper water at 630 masl. For such scenario, for which we think that is most probable in the future period, the crest settlements in the sand dam can be expected approximately of 50-60 cm. The third scenario is by transformation of the consolidation pressure in steady pore pressure for seepage at constant level of upper water at 652 masl. For such scenario, due to the material swelling from the upstream water saturation, by the mathematical model (due to the elastic response of the materials) a rising of the material would be occurred for approximately 20 cm.

Having in consideration the consolidation settlements in the post-service period, according to scenario no. 2 (for which we think that most probably will occur in future), as well and material creep deformations, that can not be modelled yet on satisfactory way, we recommend heightening in crest of dam no. 2-2 at elevation 654.0 masl to be 1.0 m. Such value of 1.0 m will be for the mediate part with greatest height of the dam, and for remaining parts from the mediate zone towards the valley banks, such heightening is linearly decreased to value of 0.0 m.

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