COMPARISON ANALYSIS OF THE BEHAVIOR OF ROCK-FILL DAMS WITH CLAY CORE AT THE VARIATION OF WATER LEVEL IN THE RESERVOIR

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ABSTRACT

By application of advanced numerical methods, the behavior of embankment dams is successfully analyzed, almost for all typical states of static loading. The occurrences, not fully clarified during the static analysis of some types of embankment dams, are caused by the water effect. Such occurrences include: (a) hydraulic fracturing phenomenon of the coherent material (earth dams and earth-rock dams) during full reservoir with established steady seepage and (b) appearance of softening and weakening (or the latest term collapse settlement) of the rock material at the upstream dam shell in case of rock-fill dams with core, during the rapid filling of the reservoir. The topic of the research, whose results are included in the paper, is clarification of the stress-strain state for rock-fill dams with central waterproof element at variation of the water level in the reservoir. This issue, stated in the dam engineering in 70's of the last century, was analyzed in several occasions, but the general conclusion is that the effect of water saturation of the rock material is not fully explained. In this paper are presented results from the comparison analysis of the variation of the water level of the reservoir, formed by construction of Kozjak Dam, on the river Treska, a tributary of the river Vardar. It is a rock-fill dam with slightly inclined clay core, with structural height of 130.0 m, the highest dam in the Republic of Macedonia. The first filling of the reservoir took place in 2003-2004 and the dam behavior was monitored by surveying methods and by installed instruments in the dam body.

INTRODUCTION

By applying contemporary numerical methods, based on Finite Element Method (FEM), the mathematical models for successful research of the behavior of fill dams are developed, almost for any typical state of static loading. The only occurrences that are yet to be fully clarified at static analysis of fill dams are those caused by the water effect. These include the possible occurrence of hydraulic fracturing phenomenon in coherent materials (within earth and earth rock dams) at the stage of full reservoir through established steady seepage flow, and the possible softening and weakening (or collapse settlement) of the rock material in the upstream dam shell in case of rockfill dams with core during the stage of reservoir rapid filling.

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The objective of this research, is to clarify the stress-deformation state of rockfill dams with central impermeable element during variation of the water level in the reservoir. This issue, raised in dam engineering since the 1970s, was investigated on several occasions, but all attempts ended by stating that the modeling was not properly done and according to the latest knowledge in this field. The general conclusion is that the saturation effect of the rock material is still present. The aim of this paper is to contribute to the selection of most favorable numerical models for simulation of the response of embankment dams with shells of rock material and core of coherent material under the effect of variation of the water level in the reservoir. To accomplish the specified goal, a comparison of few models has been done, differing by the constitutional laws for the stress-strain dependence. The contribution of this research refers to the recommendations of more advanced numerical model for study of the stress-deformations state in case of rockfill dams with core during the stage of rapid filling of the reservoir.

THE WATER EFFECT IN CASE OF STATIC RESPONSE OF EARTH ROCK DAMS WITH CORE

The research on water effects on earth-rock dams subjected to static loading was limited until the 1970s, due to the application of the classical methods, based on Theory of elasticity and Theory of plasticity. Therefore, these methods were gradually replaced by advanced methods – Finite element method (FEM), developed in the last three decades of the twentieth century, thanks to the pioneering work in this field by Zienkiewicz and Clough (ICOLD 1978). The improvement of the calculation technique (hardware and software) in the beginning of the 21th century has enabled the advanced numerical methods, based on the FEM, to fully replace the classical methods in the engineering practice. The focus of the current research is to clarify the response of rockfill dams with earth core under the effect of variation of water level in the reservoir. The variation of water level causes various effects on the stress-strain state of the fill dams. In the following paragraphs, a short overview of water effect for typical loading states of the structure during construction and in service period is given.

During rockfill dam construction, water effects are relevant for the zones of coherent material, and can be modelled using FEM. The coherent materials are applied in layers with optimal humidity, meaning that the pores are fully filled with water. By increasing the load (through placing of the upper layers) at the first moment, the full load is accepted by the pore water and pore pressure occurs. During time, a pore pressure dissipation occurs by leaching of the water. Such slow hydrodynamic process of pore pressure release, followed by an increase of the effective stresses and material settlement is called consolidation. The FE simulation of the development (increase and dissipation) of the pore pressure is performed according to two concepts: analysis of total stresses and analysis of effective stresses. According to the first (simplified) method, a consolidation pore pressure, caused by the change of the total stresses, can be generated by application of total stresses or in non-drained conditions in case of low permeable coherent materials. The stress-deformation state, as well as the development (generation and dissipation) of the pore pressure, are most realistically determined by analysis of the effective stresses, meaning that the coherent material is treated in drained conditions. In the response of the structure according to the second approach, three components are included: (1) mechanical and elastic properties, (2) hydraulic properties (seepage coefficient and volume content of the water) and (3) time factor, or dynamic of dam construction.

For the state of reservoir filling, the water effect is most simply manifested in case of rockfill dams with facing made of artificial material. This is a case where the water is outside of the dam body and acts as external pressure. Far more complex is the response of the rockfill dams with diaphragm and earth rock dams with core of coherent material, due to the water effect. At stage of rapid filling of the reservoir, the water rapidly fills the pores of the rock material in the upstream dam shell and causes the following effects: (1) softening of the submerged non-coherent material, causing additional settlements, (2) alleviation of the permeable material (increase of the total stresses and pore pressure and decrease of the effective stresses) and (3) action of force due to the hydrostatic pressure along the upstream face of the core/diaphragm.

Similar water effects, but with opposite action, occur in the state of rapid drawdown of the water level in the reservoir. The initial state for the stage of rapid drawdown of the reservoir is the state of steady seepage, for which pore pressure generated seepage in the earth material. Lowering of the water level in the reservoir causes change of the pore pressure in the earth material. It should be noted that the lowering of the reservoir water level during a period of few days to few weeks is rapid, compared to the time consuming hydrodynamic process of slow leaching of the water from the saturated low permeable earth material. Similar to the stage after dam construction (before first filling of the reservoir), at the stage of rapid drawdown of the reservoir excess pore pressure occurs, thus initiating consolidation process (manifested by decrease of the pore pressure, raise of the effective stresses and settlements). The difference in the consolidation processes for both stages consists in the factor that causes the excess pore pressure. During construction, the excess pore pressure is caused by the loading of the upper layers, while at the stage of reservoir rapid drawdown, the variation of the boundary hydraulic conditions generates the excess pore pressure.

For the state of full reservoir, with established steady seepage through the earth material, the stresses distribution depends on the following factors: dam composition and geometry, material parameters and dam type. In case of fill dams, there is regular occurrence of stress transfer, thus enabling unloading of some elements and overloading of others. If in a particular zone, the value of the pore pressure exceeds the value of the total normal stresses, a zone with negative effective pressure occurs. It can lead to hydraulic fracturing, manifested by appearance of fissures in the coherent material. Most common reason for occurrence of hydraulic fracturing is the non-uniform settlement of zones by materials of different stiffness properties, where the softer material "hangs" on the stiffer material and thus transferring part of its stresses. The next potential reason is distinct unevenness and different inclinations in the foundation of the coherent material, causing uneven settlements and zone of shattered and unloaded material. According to Penman researches from 1975, the occurrence of the hydraulic fracturing at earth materials is possible if the pore pressure in within the interval of maximal and minimal total normal stress. According to other authors, for occurrence of the fissuring of coherent material, beside the negative effective normal pressure, an appropriate non-homogeneity of the material is required, thus referring to the finding that such phenomena is not fully clarified yet.

From the above specified short overview of the water effect at the response of dams for typical loading states in static conditions, it can be concluded that for research of the fill dams behavior (during construction and in service period) standard numerical models are distinguished. Such models are successfully applied in case of various dam types and almost for all loading states [Petkovski L., Tančev L., Mitovski S., 2007]. For most of the dams (fill and concrete) for the reservoir filling state are obtained displacements in downstream direction, which in fact is intuitively expected by the researchers. It was one of the reasons why in the past were adopted minor curving of the dam crest in layout, placing the convex face towards the reservoir, even in the case of fill dams, even though they are gravitational structures. Such solutions for earth-rock dams with central or slightly inclined core in cross section and with curved shape in layout with convex face towards the reservoir were very popular in the middle of the 20th century. Most likely, the designer's prediction was that the downstream horizontal displacement, under influence of the reservoir filling would cause additional compaction of the local material that would provide improved safety of the fill dams.

By more precise measurements of the horizontal displacements in the interior part of the dam, for the state of reservoir first filling, in case of rockfill dams with core/diaphragm is registered unusual occurrence in the cross section axis. Such occurrence, registered by inclinometer, was noted by Marshal and Ramirez in 1967, and referred on the first filling of the reservoir at El-Infiernillo Dam, Mexico [ICOLD, 1986, Bulletin 53]. Such occurrence is manifested by upstream horizontal displacement of the dam during first filling of the reservoir up to 50% of the height. The further raising of the water level in the reservoir causes downstream displacement in the lower part up to 30% of the dam height, while the crest is still displaced upstream. By reaching the normal water level in the reservoir, the dam axis is displaced in downstream direction, with maximal intensity at 50% of the dam height. Such unusual bidirectional horizontal displacement at the crest in dependence of the water level in the reservoir results from the complex water effect in the upstream shell of the rockfill dams with core. The first attempt for analysis of the displacement phenomena at rockfill dams with core during first filling was by Nobari and Duncan in 1972, where following components were superposed: water load, softening and weakening of the fill material. The softening of the local material by the saturation process is confirmed with triaxial testing for dams Oroville (USA) and Beliche, (Portugal), and in the numerical multistage experiment should be modelled by variation of the stiffness and strength parameters.

The further research (modelling and measuring) of the non-usual bidirectional horizontal displacements of rockfill dams with core, for the stage of first filling, systemized in the publications of the most authoritative institution in dam engineering worldwide [ICOLD, 1988, Bulletin 94], point out that such phenomena is not yet clarified in full. Such issue, raised in the dam engineering in the 70-ties of the 20th century was analyzed in several occasions [ICOLD, 1994, Numerical analysis of dams, Volume III] and it was stated that it is not modelled properly [ICOLD, 2001, Bulletin 122]. In the latest publications, the terms “softening and weakening” are most often replaced by “collapse settlement” [ICOLD, 2013, Bulletin 155], but the effect of the saturation of the rock material is still present.

ANALYSIS OF THE STATE OF RAPID FILLING OF EARTH-ROCK DAMS WITH CORE

The state of stress in the dam body for stage of first filling of the reservoir can be analyzed by numerical models, differing by: (a) constitutive law for the dependence stress-strain and (b) the boundary condition on where to apply the hydrostatic pressure – the upstream slope of the dam or upstream face of the waterproof element. If the boundary condition is upstream slope of the dam, a far more realistic picture is obtained for the distribution of the maximal normal stresses (total and effective), that is the base for all further structural (static and dynamic) analyses of the fill dam. Therefore, the purpose of the current research is to contribute at the choice of most favorable numerical model for simulation of the stress-deformation state in case of earth-rock dams with shells of rock material and central waterproof element, under influence of the reservoir filling. In order to achieve the specified aim a comparison of the specified particular models is done.

The comparison of the different numerical models for research of the stress state in case of fill dams during the stage of reservoir first filling is illustrated by the results from static analysis of dam Kozjak, on river Treska, right tributary of the river Vardar, Republic of Macedonia (fig. 1, 2 and 3). It is a rockfill dam with slightly inclined clay core, with structural height of 130 m, the highest dam in Macedonia. The dam was constructed in 2000, the first filling of the reservoir took place in 2003-2004 and the dam behavior was monitored by surveying methods and by installed instruments in the dam body.

Figure 1. Map of the Republic of Macedonia.

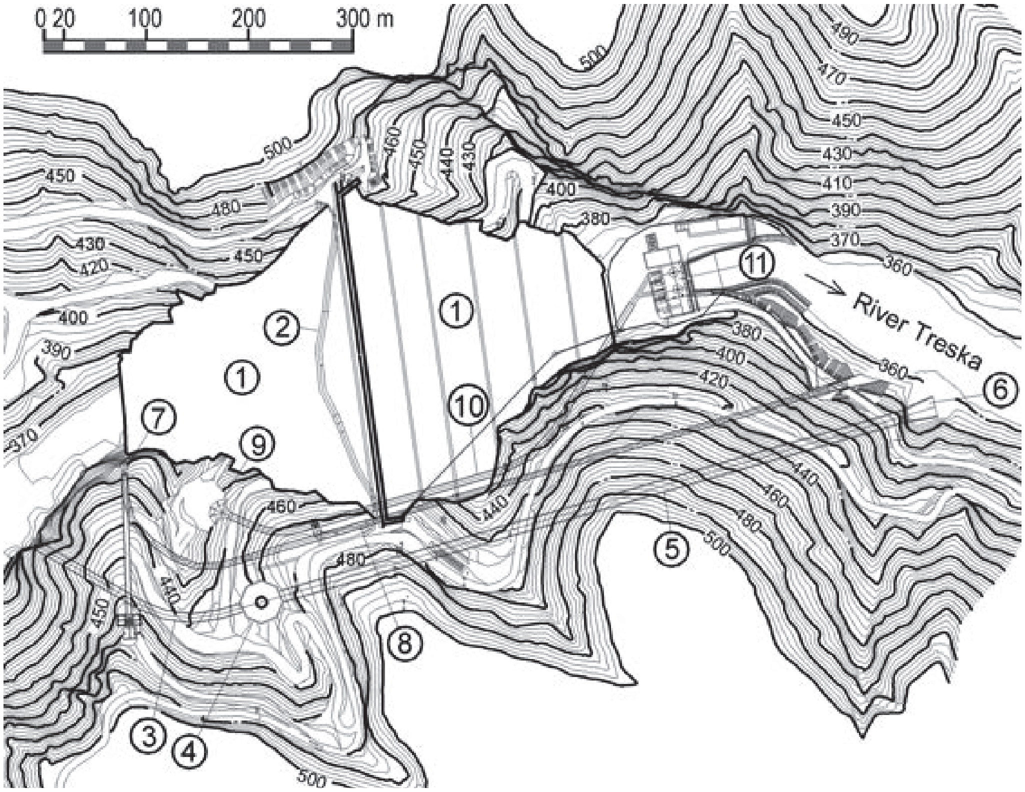

Figure 2. Layout of the hydraulic scheme with Kozjak Dam. (1) Dam body; (2) grouting gallery; (3) diversion tunnel; (4) morning glory (shaft) spillway; (5) spillway tunnel; (6) flip bucket; (7) intake structure of the bottom outlet; (8) bottom outlet tunnel; (9) intake structure of the power plant; (10) water supply tunnel for the power plant; (11) tail raise channel.

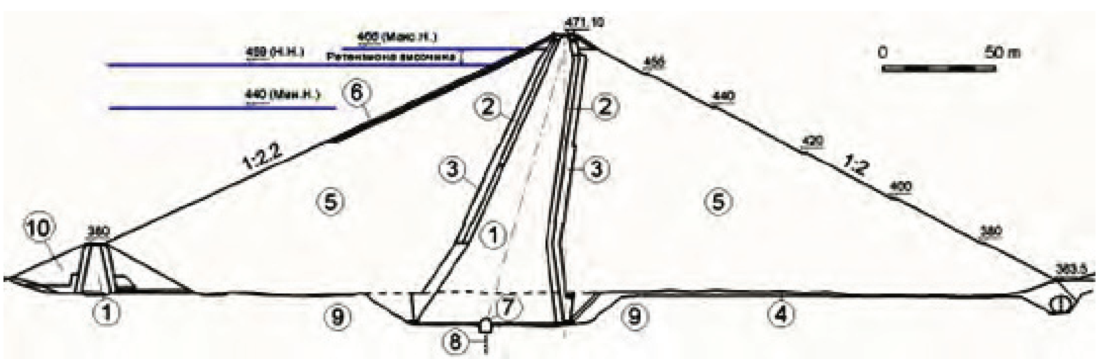

Figure 3. Main cross-section of Kozjak Dam, section no. 17. (1) Clay core; (2) first transition zone; (3) second transition zone; (4) river deposit; (5) rockfill shells (limestone); (6) arranged slope protective stones; (7) grouting gallery; (8) grout curtain; (9) rock foundation (limestone); (10) gravel in the upstream cofferdam.

NUMERICAL MODEL CALIBRATION

For calibration of the numerical model for analysis of the state of first filling are used data from technical monitoring of the dam for construction state and consolidation process of the dam. The respective strength parameters are adopted by using numerous data from control laboratorial testing of the placed local materials. The elastic parameters, by variable elasticity modulus with change of the effective stresses, are set by meeting the criteria on minimization of the difference between the measured and simulated values. The following key measured values are registered within the dam monitoring, directly after dam construction: maximal settlement of 1.3 m, maximal pore pressure at dam core foundation (400-700) kPa and crest settlement, caused by consolidation, shortly before the first filling, of 0.1 m. The typical cross section no. 17, representative for plane static analysis, is discretized with grid of 947 finite elements, connected in 947 nodes (fig. 4).

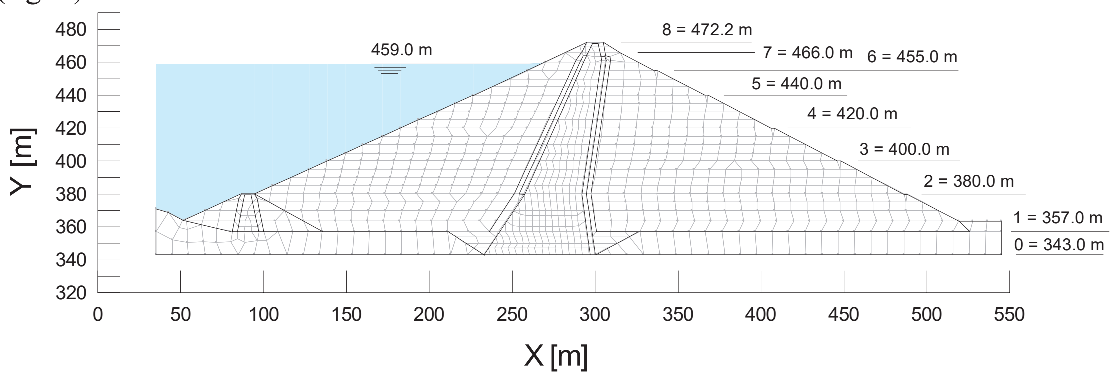

Figure 4. Numerical model for cross section no. 17, discretized by finite elements

For obtaining of the initial state before reservoir filling, a model with effective stresses is applied, by coupling mechanical and hydraulic response of the structure in real domain. The state after dam construction is simulated in 28 loading increments for period of 920 days (fig. 5). The consolidation state is simulated in one loading increment, by 14 calculation exponential steps, for period of 1,043 days. From the distribution of: settlements after construction (fig. 6), pore pressure after construction (fig. 7) and incremental consolidation settlements (fig. 8), it can be concluded that the model calibration is properly done.

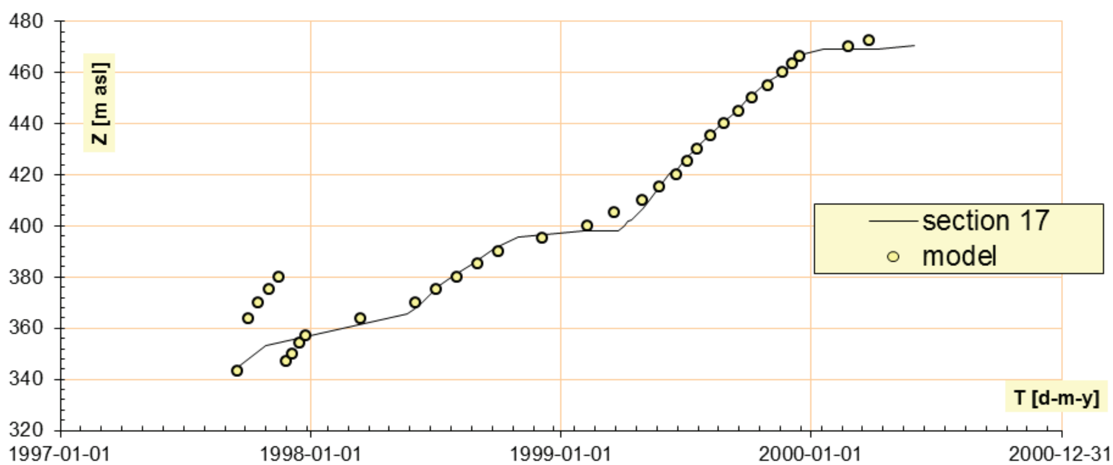

Figure 5. Dam construction simulation.

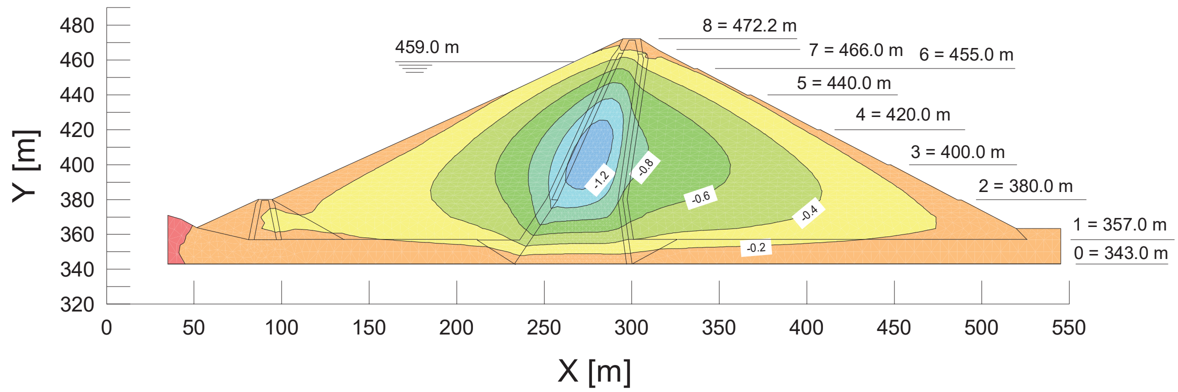

Figure 6. State after dam construction, Ydisplacement (-1.338) - (+0.012) m

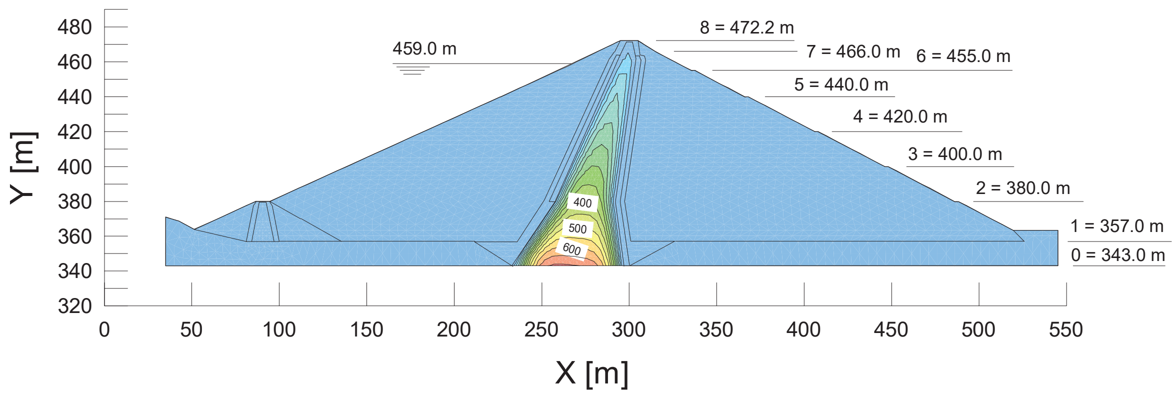

Figure 7. State after dam construction, Pore water pressure, (-0.0) - (+710.5) kPa

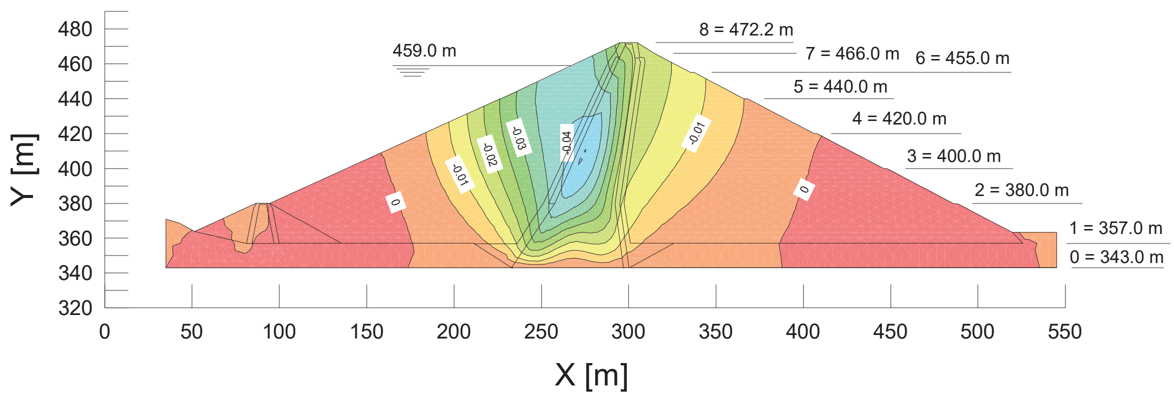

Figure 8. State upon consolidation, dY displacement (-0.045) - (+0.001) m

ANALYSIS OF THE STATE OF FIRST FILLING OF THE RESERVOIR

By using the calibrated model, the state of first filling is simulated in period of 516 days, by linear increase of 15 calculation steps of the water level from 343.0 m asl to 459.0 m asl (fig. 9). The generation and dissipation of the pore pressure in the three typical stages (fig. 10), by total lasting of 2,479 days, mostly matches with the measured values, that is contributing the conclusion regarding the regularity of the numerical experiment.

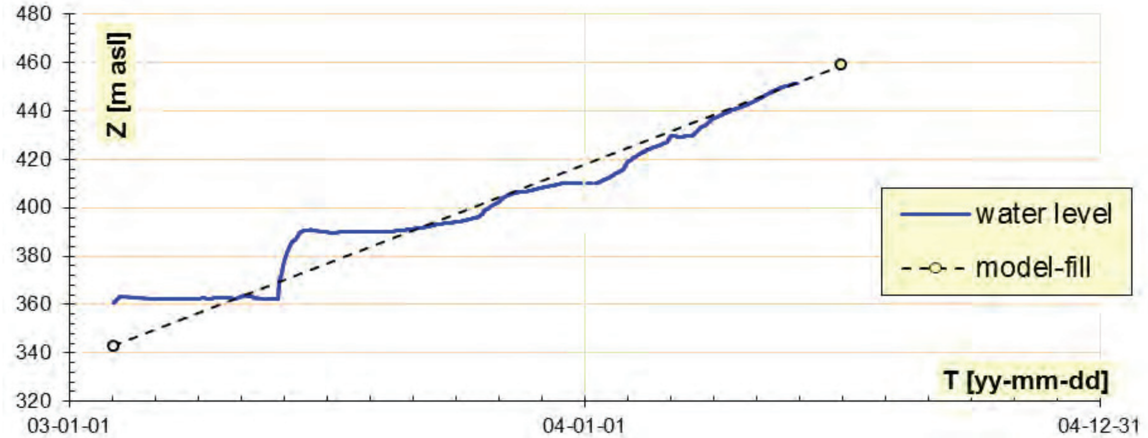

Figure 9. Simulation of the reservoir first filling

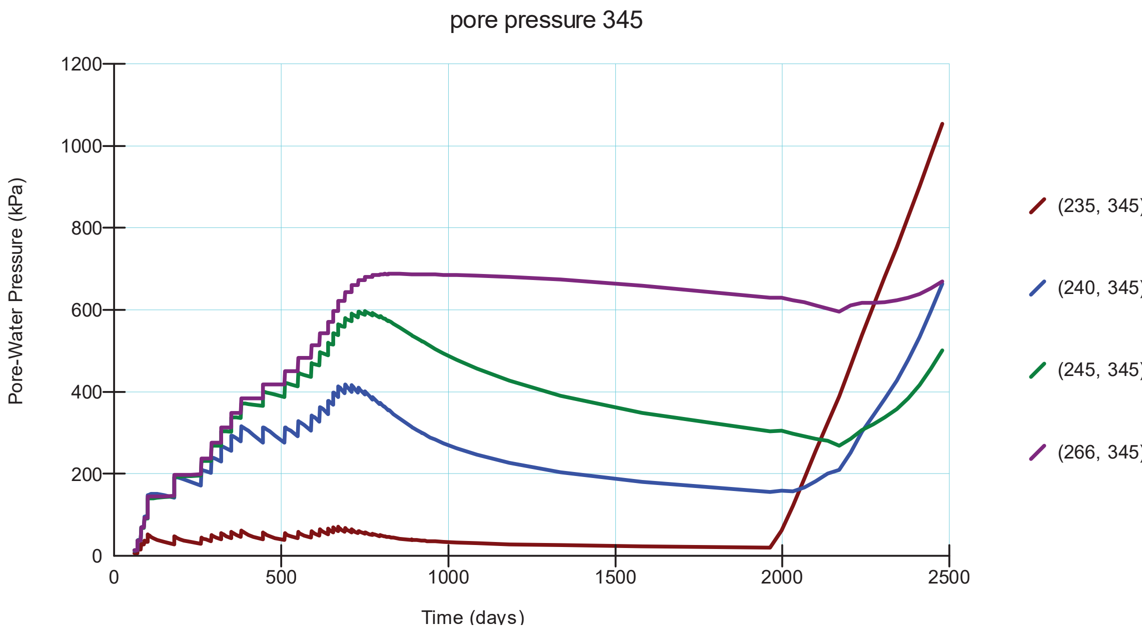

Figure 10. Generation and dissipation of the pore pressure at core foundation, at elevation 345.0 m asl, with coordinates X = {235, 240, 245, 266} m

The unusual bidirectional displacements of the central waterproof element, in dependence of the water level, are displayed for the upstream and downstream face of the core, fig. 11 and fig. 12. By the pattern and distribution of the horizontal displacements, it can be concluded that the response of the earth rock dam during first filling is properly simulated, and that the state of the effective stresses upon reservoir filling (fig. 13) can be successfully applied for analyses of the following static and dynamic loadings of the structure.

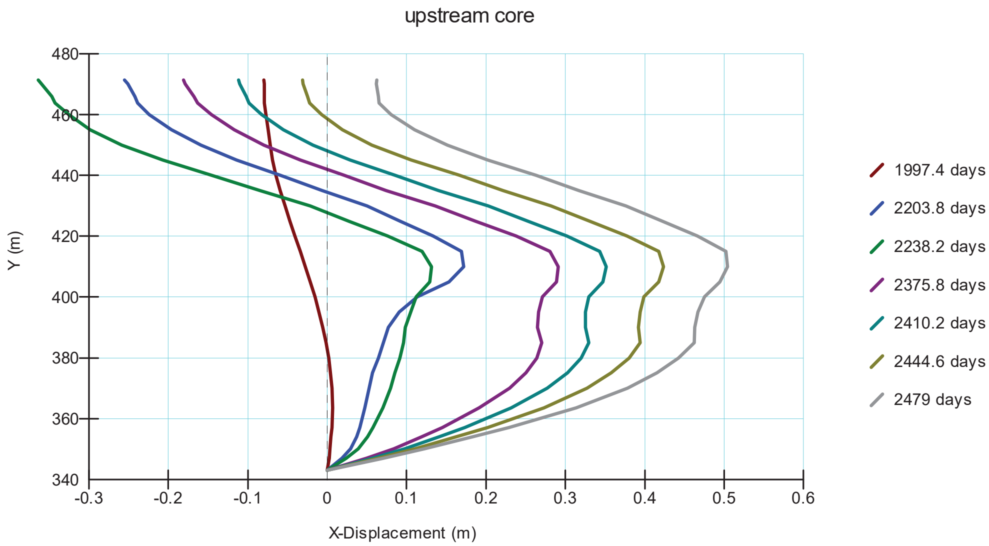

Figure 11. Development of horizontal displacements along upstream face of the core during first filling of the reservoir

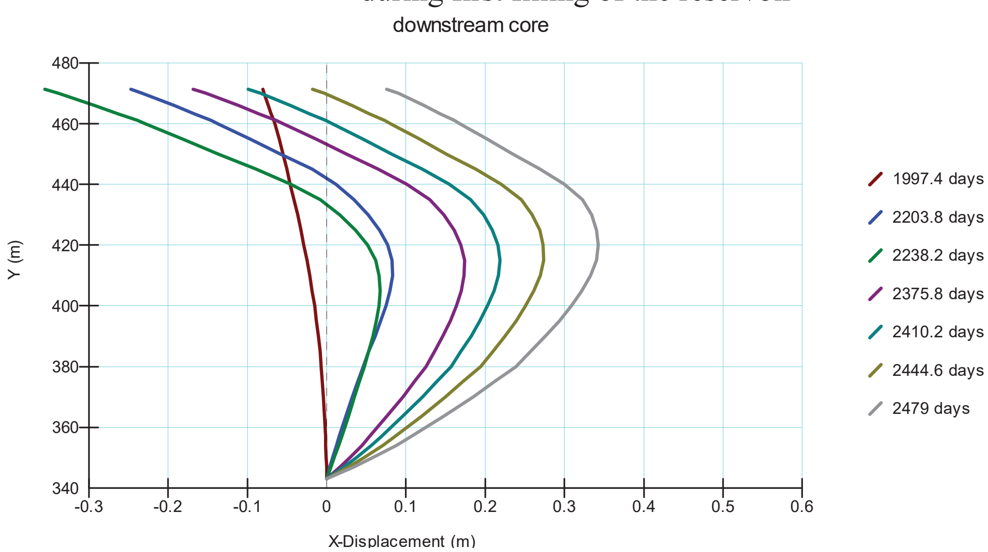

Figure 12. Development of horizontal displacements along downstream face of the core during first filling of the reservoir

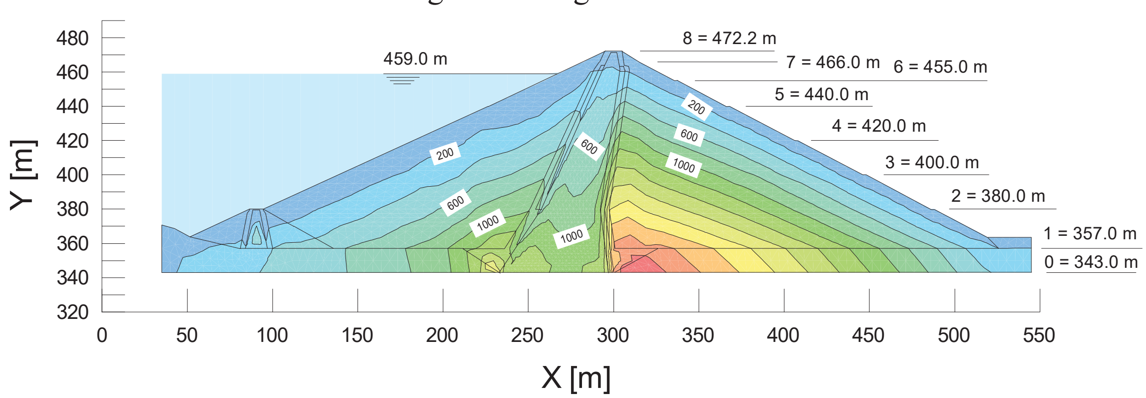

Figure 13. Distribution of effective vertical stresses, (10.14) - (+2,590) kPa after reservoir filling

The change of the total stresses results from the additional load from the increase of the volume weight and external hydrostatic pressure along the upstream slope, while the lowering of the stiffness of the rock material, due to the lowering of the effective stresses, is affecting the displacements. The effective stresses are difference of the total stresses and neutral water pressure (according to the laws of hydrostatic) in the pores of submerged materials upstream of the core. The softening of the material is actually caused by the lowering of the elasticity modulus, due to lowering of the effective stresses. The reason why in reality, by water saturation of the upstream shell (or by lowering of the effectives stresses) raising does not occur (elastic response) is the superposition of at least three effects: (a) increased stiffness at unloading, (b) downstream displacement caused by the basic load – hydrostatic pressure and (c) occurrence of "collapse settlement". The third effect is manifested by settlements of the coarse material after submerging in water, due to the decrease of its strength parameters, crushing of the grains edges - phenomena intensively researched in the last two decades [Alonso et al., 2005; Oldecop and Alonso, 2007; Roosta and Alizadeh, 2012]. The results for the partial horizontal displacements (fig. 10 and 11), where in the axis of the inclined core, the maximal horizontal displacement is approximately 40 cm in the intermediate part of the dam, and at crest approximately 10 cm, according to the pattern are similar with obtained values by monitoring of earth-rock dams with central core and are appropriate to the numerical analysis of rockfill dam Konsko (Gevgelija, Republic Macedonia) with asphalt core [Petkovski L., Tančev L., Mitovski S., 2013].

CONCLUSION

The response of fill dams to the action of static loads is a complex issue that in most cases cannot be solved by physical law, but is assessed by numerical models. The inclusion of models instead of laws means that for analysis of a dam, the models (based on different approximations) are not mutually excludible but in contrary, they contribute to a better understanding of the prototype behavior. By comparison of the results from the considered models (elastic and non-elastic, with constant and variable elasticity modulus) for the behavior of the earth rock dams with slight inclined core, during the stage of reservoir first filling, the following two observations can be outlined. First, by applying elastoplastic model with variable elasticity modulus in dependence of the effective normal stresses are obtained patterns of bidirectional displacements in the axis of the waterproof element, verified by monitoring of real structures. Second, by applying of boundary hydraulic condition along the upstream slope of the dam, a realistic distribution of the maximal main normal stresses (total and effective) is obtained, which is the base for all further structural (static and dynamic) analyses of the fill dam. Namely, this concept for displacements is in correlation with the calculated stresses, meaning they result from the change in the effective stresses, as difference between the total stresses and neutral water pressure.

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REFERENCES

Alonso, E.E., S. Olivella and N. M. Pinyol. 2005. A review of Beliche Dam, Géotechnique 55, No. 4, p.p.267–285

Geo-Slope SIGMA/W, 2012. "Stress/deformation analysis", GEO-SLOPE International Ltd., Calgary, Alberta, Canada

ICOLD, 1978, Bulletin 30, Finite elements methods in analysis and design of dams, Paris, France

ICOLD, 1986, Bulletin 53, Static analysis of embankment dams, Paris, France

ICOLD, 1988, Bulletin 94, Computer software for dams - Validation, Paris, France

ICOLD, 1994, Numerical analysis of dams, Volume III, Theme B1 "Evaluation of pore pressure and settlements of an embankment dam under static loadings", Paris, France

ICOLD, 2001, Bulletin 122, Computational procedures for dam engineering - Reliability and applicability, Paris, France

ICOLD, 2013, Bulletin 155, Guidelines for use of numerical models in dam engineering, Paris, France

Oldecop, L.A. and Alonso, E.E. 2007. Theoretical investigation of the time-dependent behaviour of rockfill. Géotechnique, 57 (3), pp.289-301

Petkovski L., Tančev L., Mitovski S., 2007. 06 "A Contribution to the standardization of the modern approach to assessment of structural safety of embankment dams", 75th ICOLD Annual Meeting, International Symposium “Dam Safety Management, Role of State, Private Companies and Public in Designing, Constructing and Operation of Large Dams”, 24-29 June 2007, St.Petersbourg, Russia, Abstracts Proceedings p.66, CD-ROM

Petkovski L., Tančev L., Mitovski S., 2013.10 "Comparison of numerical models on research of state at first impounding of rockfill dams with an asphalt core", International symposium, Dam engineering in Southeast and Middle Europe - Recent experience and future outlooks, SLOCOLD, 16-17.10.2013 Ljubljana, R.Slovenia, ISBN 978-961-90207-9-1, Proceedings, 106-115

Roosta M. R., and Alizadeh A. 2012. Simulation of collapse settlement in rockfill material due to saturation. International Journal of Civil Engineering, Vol. 10, No. 2, June 2012, pp.93-99

