Role of Dams and Reservoirs in a Successful Energy Transition

Robert M. Boes
Patrice Droz
Raphaël Leroy

CRC Press
Taylor & Francis Group

ROLE OF DAMS AND RESERVOIRS IN A SUCCESSFUL ENERGY TRANSITION

Today, new and unexpected challenges arise for Europe's large array of existing dams, and fresh perspectives on the development of new projects for supporting Europe's energy transition have emerged. In this context, the 12th ICOLD European Club Symposium has been held in September 2023, in Interlaken, Switzerland. The overarching Symposium theme was on the "Role of dams and reservoirs in a successful energy transition". The articles gathered in the present book of proceedings cover the various themes developed during the Symposium:

– Dams and reservoirs for hydropower
– Dams and reservoirs for climate change adaptation
– Impact mitigation of dams and reservoirs
– How to deal with ageing dams

In conjunction with the Symposium, the 75th anniversary of the Swiss Committee on Dams offered an excellent opportunity to not only draw from the retrospective of Switzerland's extensive history of dam development, but to also reveal perspectives on the new role of dams for a reliable and affordable energy transition. These aspects are illustrated by several articles covering the various activities, challenges, and concerns of the dam community.

PROCEEDINGS OF THE 12TH ICOLD EUROPEAN CLUB SYMPOSIUM 2023 (ECS 2023, INTERLAKEN, SWITZERLAND, 5-8 SEPTEMBER 2023)

Role of Dams and Reservoirs in a Successful Energy Transition

Edited by

R.M. Boes, P. Droz & R. Leroy

Swiss Committee on Dams

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A BALKEMA BOOK

Front Cover Image: David Birri

First published 2023
by CRC Press/Balkema
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

and by CRC Press/Balkema
2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

Typeset by Integra Software Services Pvt. Ltd., Pondicherry, India

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record has been requested for this book

ISBN: 978-1-032-57668-8 (hbk)
ISBN: 978-1-032-57671-8 (pbk)
ISBN: 978-1-032-44042-0 (ebk)
DOI: 10.1201/9781003440420

Members of the 12th ICOLD European Club Symposium Scientific Committee

Aufleger Markus	Austria
Balestra Andrea	Switzerland
Balissat Marc	Switzerland
Baumer Andrea	Switzerland
Boes Robert	Switzerland
Carstensen Dirk	Germany
Conrad Marco	Switzerland
De Cesare Giovanni	Switzerland
Droz Patrice	Switzerland
Ehlers Stefan	Switzerland
Erpicum Sébastien	Belgium
Favero Valentina	Switzerland
Fielding Mark	Ireland
Fry Jean-Jacques	France
Gunn Russel	Switzerland
Humar Nina	Slovenia
Jovani Arjan	Albania
Leroy Raphaël	Switzerland
Mazzà Guido	Italy
Mouvet Laurent	Switzerland
Otto Bastian	Switzerland
Petkovski Ljupcho	North Macedonia
Pinheiro Antonio	Portugal
Ruggeri Giovanni	Italy
Schleiss Anton	Switzerland
Sliwinski Piotr	Poland
Wieland Martin	Switzerland
Yang James	Sweden

PROCEEDINGS OF THE 12TH ICOLD EUROPEAN CLUB SYMPOSIUM 2023 (ECS 2023, INTERLAKEN, SWITZERLAND, 5-8 SEPTEMBER 2023)

Role of Dams and Reservoirs in a Successful Energy Transition

Edited by

R.M. Boes, P. Droz & R. Leroy

Swiss Committee on Dams

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A BALKEMA BOOK

Front Cover Image: David Birri

First published 2023
by CRC Press/Balkema
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

and by CRC Press/Balkema
2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

Typeset by Integra Software Services Pvt. Ltd., Pondicherry, India

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record has been requested for this book

ISBN: 978-1-032-57668-8 (hbk)
ISBN: 978-1-032-57671-8 (pbk)
ISBN: 978-1-032-44042-0 (ebk)
DOI: 10.1201/9781003440420

Role of Dams and Reservoirs in a Successful Energy Transition – Boes, Droz & Leroy (Eds)
© 2023 The Author(s), ISBN 978-1-032-57668-8

Safety of embankment dams in the case of upgrading the existing tailings storage facilities

L. Petkovski, F. Panovska & S. Mitovski
Faculty of Civil Engineering, Ss. Cyril and Methodius University in Skopje, Skopje, North Macedonia

ABSTRACT: The embankments over tailings dams and waste lagoons or the upgrade at the existing tailings storage facilities, from stability aspects of a heterogenic geo environment, has many similarities with the tailings dams with upstream construction method. These earth-fill structures are susceptible to liquefaction during static and dynamic (cyclic) loading and therefore they are civil engineering structures with the highest stability risk. The need to provide an additional volume for depositing tailings material, necessary for the regular operation of mines in conditions of spatial limitation, actualizes the upgrade of the tailings storage facilities. This upgrade is characterized by detailed geotechnical in-situ investigations and sophisticated structural analyses, which are illustrated by the results of the stability analyses (in static and dynamic conditions) of a dry stacking embankment above the tailings storage facility Sasa no. 2, Makedonska Kamenica, Republic of North Macedonia.

1 UPGRADING OF EXISTING WASTE LAGOONS

During the utilization of tailings storage facilities (TSF), flotation tailings with hydro transport (usually gravitational pulp duct) are conducted to the crest on the tailings dam. There, with hydro-cycloning, tailings separate into two fractions. With the coarser, or dry fraction (cycloned sand), the dam body is constructed, and the finer fraction (cyclone mud) is deposited in the waste lagoon. According to the method of advancement or construction of the tailings dams, three methods are used: downstream, central and upstream method, Figure 1.

Previous practice has confirmed that the highest stability of the tailings dam is achieved with the downstream method of advancement. In that case, the crest of the dam is moved downstream and the cycloned sand is deposited in sloping layers along the downstream slope over the tailings sand embankment. The lowest stability of the heterogeneous geoenvironment is obtained by the upstream method of stage advancement. Then, in each subsequent stage, the crest of the sand dam is displaced upstream, that is, the sand dams are founded on top of deposited tailings mud.

Heterogeneous geoenvironment - a tailings dam above a waste lagoon or a tailings dam with upstream construction method is subject to liquefaction under static and dynamic (cyclic) loading. Static liquefaction (Petkovski et al., 2019) is possible: (a) with an additional external load that causes an increase in shear stress, where the state of stress in the (q-p') diagram moves 'up' to an intersection with the failure surface, and/or (b) with an additional water saturation and reduction of the effective normal stresses, where the stress state in the (q-p`) diagram moves 'to the left' to the intersection with the failure surface. Dynamic liquefaction (Petkovski et al., 2018) occurs during an earthquake, where cyclic loading causes a continuous increase in pore pressure, which results in decrease in effective stresses, where the state of stress in the (q-p`) diagram moves 'to the left' to the intersection with the failure surface. When liquefaction occurs, the structure of the grains is destroyed and the shear strength of the material decreases to steady-state strength. Therefore, tailings dams with upstream construction method are treated as hydraulic structures with highest risk and are not recommended in

DOI: 10.1201/9781003440420-102

seismically active regions. In some countries with high seismicity, for example in Chile and Peru, the construction of tailings dams with upstream progress is prohibited by law.

The upgrading of waste lagoons in existing TSF, from the aspect of the stability of the heterogeneous geoenvironment, has great similarities with tailings dams constructed with the downstream method. The key difference consists in the fact that the period with hydrotransport of the pulp has ended and the waste lagoon of the TSF has been formed up to the final elevation. For the operation of the mine in the future period, if there is no space for a new waste lagoon, that is, there is no hydrotransport of tailings, then, for the pulp from the flotation plant a method with pressing and filtering is applied, which results in 'dry stacking'. If the upper surface of the existing waste lagoon is used as a foundation for dry stacking, due to the existence of excess pore pressure inside the lake of poorly permeable tailings mud, a standard solution is dissipation of pore pressure, Figure 2.

A logical question arises – where does the need come from for the mining companies to initiate solutions with upgrades over the existing waste lagoons? It is obvious that they are embankment constructions with highest risk, and to confirm their stability, detailed geotechnical research and sophisticated structural (static, seepage, dynamic) analyses are necessary, that would result in large financial investments. The explanation, in our opinion, is as follows. On one hand, space for the survival, development and growth of mining companies, which are essential for the existence of the population in certain regions (which rely on the mining industry), due to the imposition of increasingly strict environmental and sociological criteria, is becoming more and more limited. On the other hand, obtaining permission to expand the concession area (or increase the industrial scope) from a huge number of agencies/institutions, in countries that are heavily bureaucratized and, unfortunately, corrupt, for mining companies is prolonged in a long-term exhausting administrative process with uncertain outcome. Therefore, mining companies increasingly decide on solutions for risky hydraulic structures, i.e. embankment structures over existing waste lagoons.

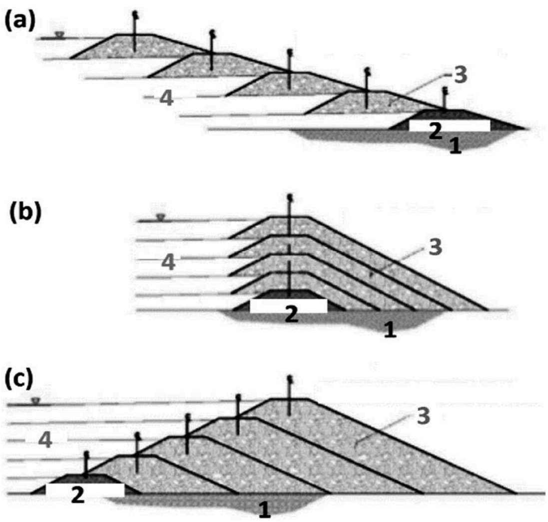

Figure 1. Methods for construction of tailings dams: (a) upstream, (c) central, (c) downstream. 1 – Foundation, 2 – starter dam, 3 – cycloned sand, 4 – cycloned mud.

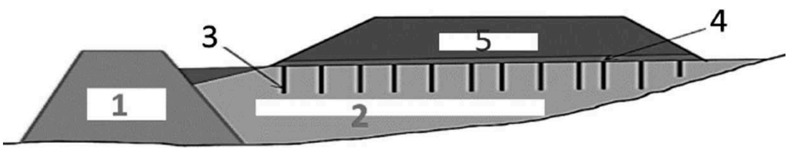

Figure 2. Upgrade to existing waste lagoon with dry stacking. 1 – Existing dam, 2 – existing waste lagoon, 3 – wick drain, 4 – granular bedding, 5 – dry stacking.

2 UPGRADING OF EXISTING WASTE LAGOONS IN RN MACEDONIA

Examples of upgrades on existing waste lagoons (or high-risk hydraulic structures) also exist in RN Macedonia, of which we will single out three, part of mining companies ‘Buchim’ - Radovish, ‘BulMak’ - Probishtip and ‘Sasa’ - M. Kamenica.

Tailings storage facility Topolnica of ‘Buchim’ copper mine, Radovish, has been in use since 1979. In the past period, in TSF Topolnica, more than 130 million m^3 of tailings have been deposited, as well as 9 million m^3 of stored water. This tailings dam is characterized by construction in phases and a combined construction method, with downstream advancement in first phase and upstream construction during the upgrade in height from the second phase, conducted in two stages (Petkovski et al., 2018). The construction of the sand dam in the initial phase, up to the elevation of 610 masl (1st phase), was carried out in sloped layers, with advancement in downstream direction from the initial dam, with an elevation at the foundation of 518.5 and crest elevation at 558.5 masl. Then, the construction of the sand dam up to the elevation of 630 masl (2nd phase, stage 1), due to the proximity of the village Topolnica to the downstream toe of the dam, was carried out with upstream construction method. In the final stage, the crest elevation is finalized at 654.0 masl (2nd phase, stage 2), with advancement in upstream direction, Figure 3 (Faculty of Civil Engineering, 2018). TSF Topolnica, with height of the tailings dam 2-2 above foundation at the initial dam of H_0 = 654.0 - 518.5 = 135.5 m, is one of the highest tailings dams in Europe. The final tailings dam 2-2 height, measured from the crest to the downstream toe, is H_2 = 654.0 - 512.8 = 141.2 m, with which this dam represents the highest dam in RN Macedonia (Petkovski et al., 2019.09).

‘Toranica’ mine in the city of Kriva Palanka (BulMak) currently operates with ore production of about 320,000 t/year, and for the needs of the production, the existing TSF is in function. The waste lagoon and tailings dam were formed with construction of an upstream and a downstream dam. The upstream (or retention) dam is conventional dam (earthfill dam with clay facing) with crest at elevation of 977.5 masl. The downstream dam is tailings dam constructed with the downstream construction method, using cycloned sand. The existing TSF Toranica has been upgraded in height twice. The first upgrade was up to crest elevation of 900.0 masl. The retention dam was upgraded with a tailings dam, constructed with central construction method, with crest displaced from the conventional dam, founded on the waste lagoon at position ‘A’. The second upgrade which is in construction phase, was designed up to elevation of 1000 masl, in accordance with the latest technical documentation for the ‘Toranica’ mine tailings dam (Geing KUK, 2018). With this design, the retention dam was planned to be upgraded in height with tailings dam, up to crest elevation of 1000 masl, made of cycloned sand with central construction method, founded on the waste lagoon, at position ‘B’. Alternative solution preparation is ongoing for the upgrade in height up to 1000 masl of the upstream dam (DIPKO, 2022), Figure 4, with location near ‘A’.

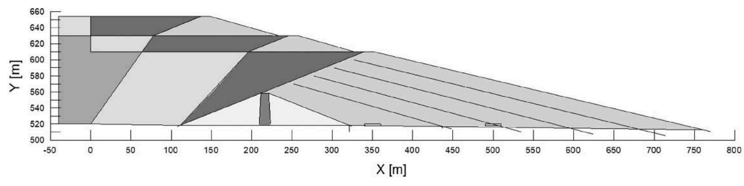

Figure 3. Construction of the tailings dam up to the elevation of 654 masl (2nd phase, stage 2).

In the past service period of TSF of the ‘Sasa’ mine in M. Kamenica, they were intended for disposal of the flotation tailings obtained by the technological process of flotation of lead and zinc minerals. It was transported by hydrotransport to the crests of the tailings dams in a cascade system along the river Kamenichka Reka: 1, 2, 3-1, 3-2 and 4 (during the period when they were active), from where, with the process of hydro - cycloning, it was separated into two fractions. Downstream dams were built with the coarser dry fraction (sand), and the finer liquid fraction was deposited in the waste lagoons.

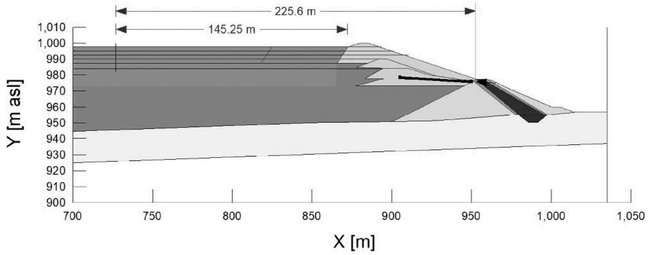

Figure 4. Sketch of the upgrade of the upstream (retention) dam of the tailings dam Toranica, according to Annex 1 of the Detailed Design from 2022 - 08 - 30.

The need to provide additional volume for depositing tailings material, necessary for the regular operation of the ‘Sasa’ mine in the future, was analyzed several times by the expert team of the ‘Sasa’ mine. In July 2019, the first opportunity for disposal of tailings on the existing waste lagoons was reviewed (Faculty of Civil Engineering, 2019). In July 2020, the possibility of dry stacking of tailings, with a volume of at least 2.25 10^6 m^3, on the surface of waste lagoons 2 and a part above waste lagoon 1 was updated. Waste lagoon 2 was formed with tailings dam 2, built with a downstream construction method. and with a crest at 1015.0 masl. Upstream from Dam 2, about 3-4 decades ago, a tailings dam 2-2 with a height of 13.0 m was built, which reached the elevation of waste lagoon 2, at 1028.0 masl, upstream of dam 2-2.

The representative longitudinal and cross sections of the geoenvironment are according to the Conceptual design (Faculty of Civil Engineering, 2020), where a dry stacking embankment was adopted in 5.0 m horizontal layers, with 3.0 m berms, a slope of 1:2.5 and a final embankment crest elevation of 1070 masl. (Figure 5).

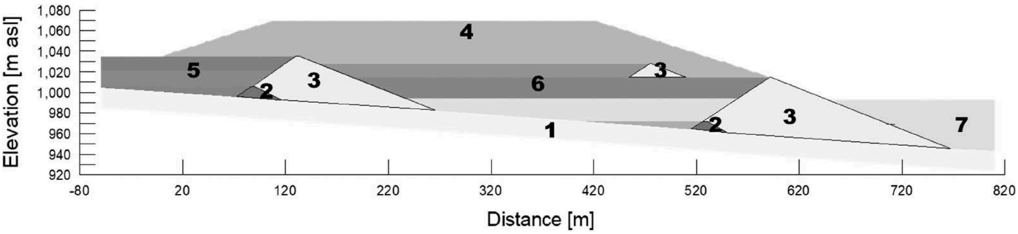

Figure 5. Representative longitudinal section, according to the Conceptual design of 2020.06.26. (1) sand and gravel (alluvium), (2) shale (initial dam), (3) sand - cycloned (dams 1, 2-1, 2-2), (4) dry disposal - embankment, (5) mud 1 - cycloned (lagoon 1), (6) mud 2 - cycloned (lagoon 2), (7) mud 3 - cycloned (lagoon 3-1).

In the further text of this paper, an overview of the key settings and conclusions from the structural analysis of the dry stacking embankment above the existing waste lagoon Sasa 2 is given, i.e. static and seepage analysis (DIPKO, 2021.09.27) and dynamic analysis (DIPKO, 2021.09.28).

3 STRUCTURAL ANALYSIS OF THE DRY DEPOSIT EMBANKMENT ABOVE THE EXISTING WASTE LAGOON ‘SASA 2′

3.1 *Basic input data for the structural analysis*

The structural (static and dynamic) analysis of the dry stacking above Sasa waste lagoon 2 is made according to the latest recommendations of ICOLD, i.e. with one mathematical model for different phases of the load, where each subsequent phase has an initial stress state determined by the previous stage.

The material in the waste lagoon 1 in the static analysis is modeled with three zones:

- from the ground at 1035 masl (crest of sand dam 1) up to 1021 masl,
- from 1021 masl up to 1,006 masl (crest on initial dam 1),

– from 1006 masl to contact with alluvium (upstream toe on initial dam 1 at elevation of 995.9 masl).

The material in the waste lagoon 2, in the static analysis is modeled with four zones:

– 2-1 from the ground at 1028 masl (crest of sand dam 2-2) up to 1015 masl (crest of sand dam 2-1),
– 2-2 from 1015 masl up to 994 masl,
– 2-3 from 994 masl to 972 masl (crest on initial dam 2),
– 2-4 from 972 masl to contact with alluvium (upstream toe on initial dam 2 at 964.5 masl).

According to the latest geotechnical investigations for tailings 1, 2 and 3-1, as well as for the material from dry disposal, systematized in the following documentation (GEING, 2020), (DIPKO, 2020), (Knight Piésold, 2021), with a larger number of SPT and CPT tests, at selected locations, the following key data was obtained:

1. Pore pressure in waste lagoons 1 and 2 is about 50% of the hydrostatic pressure.
2. Values of the coefficient of consolidated undrained shear strength S(liq)/$\sigma' v0$, obtained by CPT are:
   – For waste lagoon 2, at the surface it is 0.21, at a depth of 30 m it is 0.24 and at a depth of 45 m it is 0.26.
   – For waste lagoon 1, it is 0.21 on the surface and 0.23 at a depth of 30 m.
3. Under liquefaction conditions, the values for the coefficient Su(liq)/$\sigma' v0$, obtained by CPT are:
   – For waste lagoon 2, on the surface it is 0.04, at a depth of 30 m it is 0.12.
   – For waste lagoon 1, on the surface it is 0.10, at a depth of 20 m it is 0.05.

Under liquefaction conditions, the parameters for determining the residual shear strength coefficients Sr/$\sigma' v0$, obtained by SPT are systematized in Table 3.1.

5. For the maximum compaction (highest strength) of the embankment from dry stacking, according to data from the laboratory of the Faculty of Civil Engineering in Skopje, systematized on 27.4.2021, the optimal humidity is 10.9%, which gives a maximum dry volume weight of 21.5 kN/m^3.

Table 3.1. Parameters for determination on the coefficients on the residual strength on shear in conditions on liquefaction.

	BH1, TSF-1		BH2, TSF-2		BH3, TSF-2	
h [m blg]	7.0	21.0	6.4	23.4	12.0	25.6
FC, passing 0.075 mm [%]	48	65	65.0	91.0	23.0	35.0
N1(60-sr)	14	20	13	19	15.5	27

3.2 *Measures to improve the stability and adopted form of the geoenvironment*

The criterion for optimizing the shape of dry stacking embankment is maximization of the volume by satisfying the criteria for temporary and permanent static stability and acceptable seismic resistance of the heterogeneous geoenvironment. In the modeling, in order to fulfill the optimization criterion, stability improvement measures were gradually applied and verified.

The first measure to improve the stability of the geoenvironment is the installation of drainage carpets at the contact of the embankment of dry stacking with the existing waste lagoon 1 and 2 (at an elevation of 1035 masl upstream of dam 1, at elevation of 1028 masl upstream of dam 2-2 and at elevation of 1015 masl upstream of dam 2-1), and inside the new embankment of dry stacking – at elevation of 1050 masl. With this measure, the pore overpressure in the embankment of dry stacking during construction is practically eliminated and it is reduced in the waste lagoons. This measure has the most significant impact in improving stability and has been retained in all further variants.

A second measure to improve the stability of the geoenvironment that was considered was construction of concrete piles in the critical zones of under-toe slope instability, with the following parameters: distance between two centroids L = 1.0 m, diameter d = 0.6 m, depth H = 25 m, modulus of elasticity E = 20.0 GPa, cross section F = 0.471 m^2, moment of inertia I = 0.0064 m^4. As expected, since the piles are not anchored in a rigid environment, no improvement in stability is obtained. With the model, it was confirmed that such a measure for the geoenvironment in question has a negligible impact and was therefore not considered in the further variants.

A third measure to improve the stability of the geoenvironment that was considered was taking into account the tensile strength of the geotextile covering the drainage blanket. By applying joint elements, a geocomposite (geotextile connected to a geogrid) was modeled with the following parameters: thickness d = 4 mm, modulus of elasticity E = 1.0 GPa, cross section F = 0.008 m^2 (for two layers of geocomposite). As expected, the geocomposite can provide more uniform settlements (irrelevant for the dry stacking embankment), however, it cannot improve the overall under-toe slope stability. The model confirmed that such a measure for the subjected geoenvironment has a negligible impact on stability and was therefore not considered in further variants.

The fourth measure to improve the stability of the geoenvironment that was considered was the reduction of the load in the active zone of the critical slip surfaces. This can only be achieved by increasing the berms in the individual stages during the construction of the embankment from dry stacking, which will inevitably cause a decrease in the volume of dry stacking. This measure was considered in a larger number of variants, with a gradual increase in the widths of the berms, but also with a simultaneous check of the static stability and the seismic resistance (of the longitudinal and cross section models), in order to determine the maximum volume of the dry stacking embankment that meets the criteria for structural stability. In this way, the shape of the embankment with dry stacking was adopted (Figures 6, 7 and 8), for which the results of structural stability analysis are presented in the following text.

3.3 *Results of the static analysis*

The initial state of stresses before the start of dry stacking is determined by approximating the pore pressure distribution (Figure 9), with the 'In situ' type of analysis, thus simulating the initial state of total stresses (initial state for the next stage of loading) and effective stresses.

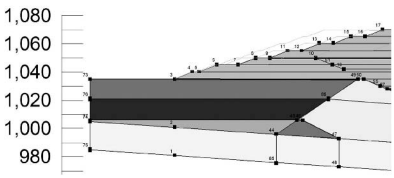

Figure 6. Upstream slope of the embankment from dry stacking (at the longitudinal section).

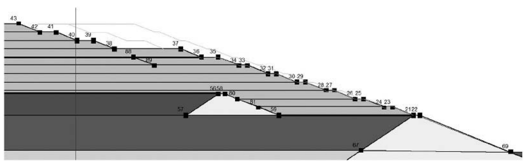

Figure 7. Downstream slope of the dry embankment tailings (at the longitudinal section).

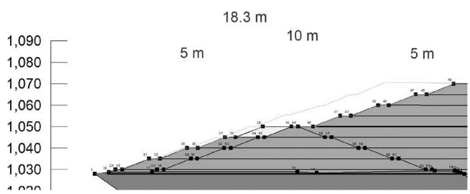

Figure 8. Left slope of the embankment of dry stacking (at the cross section).

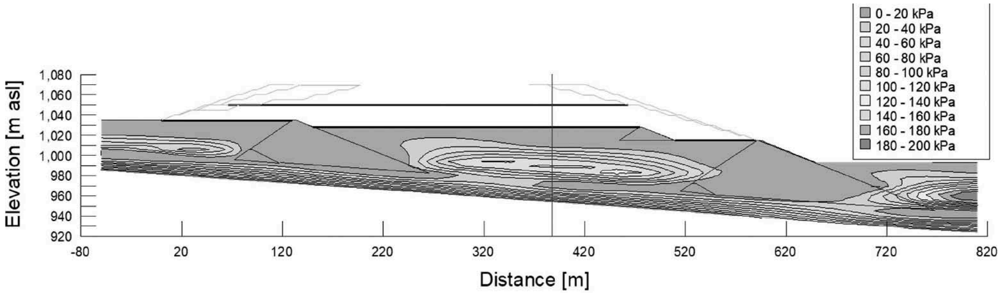

Figure 9. Approximate initial condition for the pore pressure in tailings storage facilities 1, 2 and 3-1.

The construction of the dry stacking embankment in phase 1-1 with a duration of 2.05 years is modeled in 7 stages (or load increments) with a duration of 9,226,341 sec, simulated with 10 calculation steps with an exponential time increment. This analysis was done by applying consolidation analysis of coupled mechanical and seepage response in time domain, i.e. 'Coupled Stress/PWP' type of analysis.

Finally, for phase 1-1, the stability of the upstream and downstream slope of the embankment with dry stacking was checked, using the finite element method (FEM), that is, with realized stresses from the analysis of the state of stresses and deformations. The increase in stability with pore pressure dissipation in the final stage of stage 1-1 is as follows: for downstream slope from 1.429 to 1.437, and for upstream slope from 1.341 to 1.414.

After simulating the construction of phase 1-1, phase 1-2 with a duration of 0.59 years, and phase 2 with a duration of 3.49 years are modeled, which are not visible in the model for the longitudinal section. The construction of the dry stacking embankment in phase 3 with a duration of 3.87 years is modeled in 6 stages (or load increments) with a duration of 20,336,977 sec, simulated with 10 calculation steps with an exponential time increment. At the end of this phase, the cumulative values of horizontal and vertical displacements, pore pressure and effective normal vertical stresses were determined (Figure 10). The increase in stability (expressed by the slope stability factor) with the dissipation of pore pressure in the last stage of stage 3 is as follows: for the downstream slope from 1.379 to 1.383, and for the upstream slope from 1.323 to 1.330.

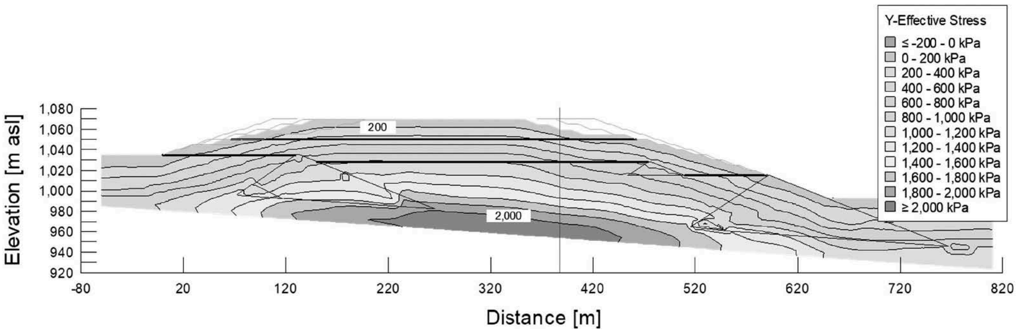

Figure 10. Effective normal vertical stresses at the end of phase 3, in tailings storage facilities 1, 2 and 3-1.

3.4 *Results of the dynamic analysis*

The selection of the parameters of the design earthquakes and the adoption of the dynamic parameters are taken from a suitable seismological data base (IZIIS - Skopje, 2020.10). The usual procedure for analyzing the dynamic response of embankment dams with reservoirs is to conduct it with at least three different accelerograms, for two levels of seismic excitation: (1) operating basis earthquake - OBE and (2) safety evaluation earthquake – SEE. In the subject analysis of a dry stacking embankment where there is no danger of sudden and uncontrolled reservoir emptying caused by potential crest damage, a simplified procedure was adopted, with one synthetic accelerogram for three levels of excitations, whereas in the analyses, a basic design earthquake is also added - DBE (Design Basis Earthquake), with a repetition period of T= 475 years, which is used for paramount constructions that do not cause a potential danger to the environment.

The dynamic response of the geoenvironment, during SEE with PGA 0.36 g and PGAy = 0.25 g, duration of t =20 s, with synthetic accelerogram T=10,000_1, is given in Figures 11, 12, 13 and 14. A visual check that the dynamic response is correct is the diagram of the relative horizontal displacements. The permanent vertical displacement, caused by the inertial forces during the uplift which is relevant for the assessment of the seismic resistance of the dam 2-1 with crest at elevation at 1015 masl, is the crest settlement of 22 cm.

During the earthquake, there is an increase in the pore pressure, which creates a liquefaction zone after the earthquake (Figure 15). The occurrence of liquefaction will cause a redistribution of effective stresses, which will result in post-earthquake displacements in the geoenvironment. In the following text, Figure 16 shows the critical slip surface for the downstream slope in the post-earthquake phase.

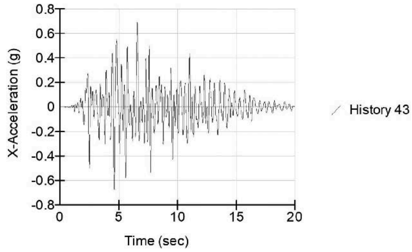

Figure 11. Absolute accelerations a[g] ÷ t[s] in horizontal direction, downstream crest of dry stacking embankment.

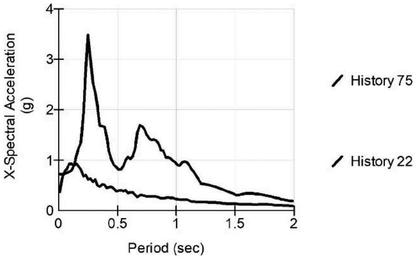

Figure 12. Response spectrum of accelerations Sa [g] ÷ T [s] for DR = 0.05, in the bedrock (excitation) and in the crest of dam 2-1 (response).

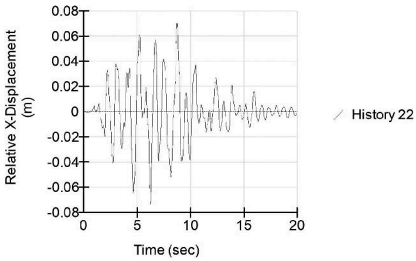

Figure 13. Relative displacements, horizontal x[m] ÷ t[s], in the dam crest 2-1.

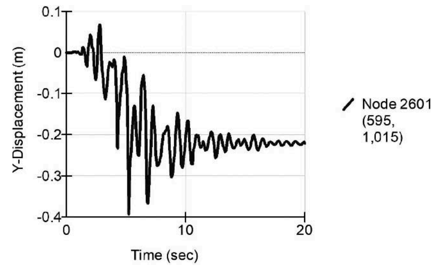

Figure 14. Permanent vertical displacements, by dynamic deformation method, Y[m]÷t[s], in dam crest 2-1.

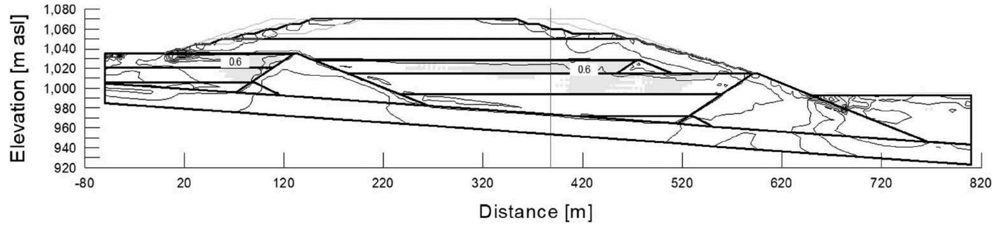

Figure 15. Distribution of the coefficient q/p' [-] with a liquefied zone, for the state of stresses at the end of the earthquake action.

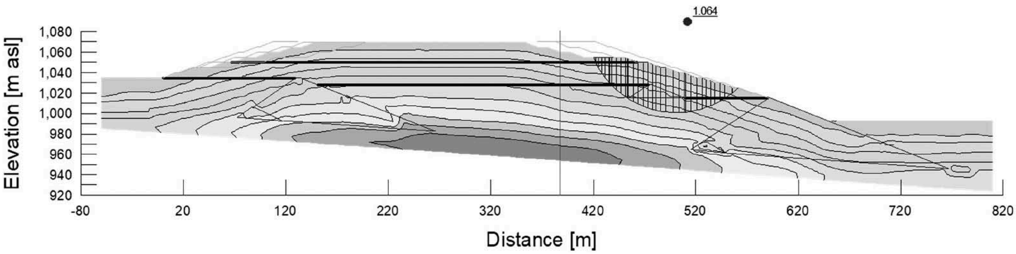

Figure 16. Critical slip surface for the downstream slope, in the post-earthquake phase.

4 CONCLUSIONS

After reviewing the results, we can conclude that the static and dynamic stability of the dry stacking embankment with the defined shape (berm sizes at the appropriate elevations) are satisfied, and we highlight the following conclusions:

1. The construction of two sub-phases 1-1 and 1-2 must be realized in one phase 1, with filling in horizontal layers, because a separate construction of phase 1-1 does not have satisfactory temporary stability of the left slope.
2. If during the construction of the combined phases 1-1 and 1-2 (that is, phase 1) temporary instability towards the right slope is noticed, then phases 1 and 2 should be filled simultaneously.
3. Pseudostatic stability under the action of a strong earthquake is not satisfied for any slope (downstream, upstream and left) of the dry stacking embankment. Therefore, the seismic resistance of the geoenvironment must be investigated and verified by dynamic time domain analysis taking into account the liquefaction phenomenon.
4. Maximum acceleration in the crest at 1015 masl of dam 2-1 (determined by longitudinal section analysis) is 0.23 g (for OBE), 0.41 g (for DBE), and 0.70 g (for SEE).
5. Maximum acceleration in the crest at 1070 masl of the dry stacking embankment (determined by cross-sectional analysis) is 0.22 g (for OBE), 0.40 g (for DBE) and 0.45 g (for SEE).
6. Permanent vertical displacement, caused by the inertial forces during the excitation, which is relevant for the assessment of the seismic resistance of the dam 2-1 with a crest at 1015

masl (determined by longitudinal section analysis) is the crest settlement, and is 0 cm (for OBE), 0 cm (for DBE) and 22 cm (for SEE),

7. With the dynamic response of the representative sections (longitudinal and cross section), for a level of seismic excitation OBE with PGA = 0.07 g with a repetition period T = 145 years, liquefaction occurs in the waste lagoons Sasa 1 and Sasa 2.
8. Minimum values of the safety coefficient in the post-earthquake phase (determined by analysis of the longitudinal section) are Fs =1.064 ≤ F = 1.1 (for the downstream slope) and Fs =1.237 > F = 1.1 (for the upstream slope) for OBE, DBE and SEE.

REFERENCES

DIPKO – Skopje, 2021.09.27, Detailed design for dry disposal above TSF 2 and TSF 1 of the mine Sasa, M. Kamenica, Book 2. Static analysis of dry disposal above TSF 2, L. Petkovski (responsible designer) et al.

DIPKO – Skopje, 2021.09.28, Detailed design for dry disposal above TSF 2 and TSF 1 of the mine Sasa, M. Kamenica, Book 3. Dynamic analysis of dry disposal above TSF 2, L. Petkovski (responsible designer) et al.

DIPKO - Skopje, 2022.08.30, Design for upgrading the retention dam from elevation 993.5 to elevation 1000.0 masl at TSF Toranica, K. Palanka (Annex no. 1 of the Detailed design for upgrading the retention and tailings dam from 986.5 to 1000 m above sea level on TSF Toranica), L. Petkovski (responsible designer) et al.

DIPKO, Skopje, 2020-11-25, Geotechnical Investigation Report from SPT and CPTu performed at Sasa tailings dams, Jovan B. Papic (responsible researcher)

Faculty of Civil Engineering - Skopje, 2018.09, Innovative seismic resistance analysis of TSF Topolnica, for variable height of operating level in the waste lagoon from 649.0 to 652.0 masl, with an estimate of maximum tailings storage in the waste lagoon (Annex no. 4 of the Construction design of TSF Topolnica, Buchim, with crest at 654.0 masl), L. Petkovski (responsible designer), et al.

Faculty of Civil Engineering - Skopje, 2019.07.23, Technical solution for dry disposal of tailings above waste lagoons, with a preliminary assessment of the stability of the tailings dams of the mine Sasa, M. Kamenica, L. Petkovski (responsible designer), et al.

Faculty of Civil Engineering - Skopje, 2020.06.26, Conceptual design for additional volume for dry stacking disposal at TSF 2 and 3-2 of the mine Sasa, M. Kamenica, L. Petkovski, (responsible designer), et al.

Geing - Skopje, 2018-09-12, Detailed design for upgrading the retention and sand dam from 986.5 m above sea level to 1000 m above sea level at TSF Toranica - K. Palanka, Natalija A. Bozhinovska (responsible designer)

Geing KuK - Skopje, 2020.09.29.Elaboration of additional geotechnical investigation works and laboratory investigations of TSF 2 – SASA Mine, S. Georgievski (responsible researcher)

IZIIS - Skopje, 2020.10, Seismic hazard study for the SASA-2 profile, Report 2020-59, D. Dojchinoski (responsible researcher) et al.

Knight Piésold, London, 2021-05-12, File No.: LO501-00057/05-03, CPT ground investigation on TSF 1 and TSF 2 at the Sasa Lead and Zinc Mine in North Macedonia, Joel Slater (responsible researcher)

Petkovski L., Mitovski S., 2018.04 'Numerical analysis if displacements in the post-exploitation period of tailings dams with a combined construction method', Topic - Tailings Dams, USSD 38th Annual Meeting and Conference, A balancing Act: Dams, Levees and Ecosystems, April 3- May 4, 2018, Miami, Florida, USA, CD Proceedings

Petkovski L., Mitovski S., 2018.07, 'Assessment of seismic resistance of combined tailings dams', 26. Congress on Large Dams, ICOLD, 1–7 July 2018, Vienna, Austria, CD Proceedings Q.101-R.58, p.978–991

Petkovski L., Mitovski S., 2019.05, 'Application of SPT Results On Liquefaction Phenomenon Modeling Of Tailings Dam', 3-rd International Symposium on Dams and Earthquakes, organized by WGDE-EC-ICOLD and PCOLD, ISBN: 978-972-49-2308-6 Proceedings, p.209–220, (6-8).05.2019, Lisbon, Portugal

Petkovski L., Mitovski S., 2019.09 'An analysis of the waste lagoon water level influence on the liquefaction resistance of the tailings dams', 11th ICOLD European Club Symposium, 'The future of Dams (in Europe): Prospects and Challenges in a changing Environment', CD Proceedings - Session 8: Advances in dam engineering: modelling, 2-4 October 2019, Chania, Crete, Greece