12th East Asian Area Dam Conference

Proceedings of the International Symposium on

SUSTAINABLE DEVELOPMENT AND MANAGEMENT OF DAMS AND RESERVOIRS FOR FUTURE GENERATIONS

June 3rd to 7th, 2024, Nagoya, JAPAN

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Stability analysis and required geometrical modification of tailings dam heightening subject to static liquefaction

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ABSTRACT: 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 heightening of the tailings storage facilities. The upgrade of the existing tailings storage facilities, with the upstream construction method of a new tailing sandy dams over the existing waste lagoon, is a heterogenic geo environment that is susceptible to liquefaction during static and dynamic (cyclic) loading and therefore they are the civil engineering structures with the highest stability risk. This upgrade is characterized by detailed geotechnical in-situ investigations, sophisticated structural analyzes (static, unsteady seepage, and dynamic), and modification of the geometry of tailings dam heightening, which are illustrated by the results of the stability investigation (in static conditions) of an upgrade of the existing up-stream diverting rockfill dam with clay core, with tailings sandy dam above the tailings deposition lake of the tailings storage facility Toranica, Kriva Palanka, Republic of North Macedonia, Europe.

1 CRITICAL STATE OF HEIGHTENING OF THE EXISTING TAILINGS STORAGE FACILITIES (TSF)

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 a tailings sand embankment. The lowest stability of the heterogeneous geoenvironment is obtained by the up-stream method of stage advancement. Then, in each subsequent stage, the crest of the sand dam is moved upstream, that is, the sand dams are founded on deposited tailings mud. Heterogeneous geoenvironment - a tailings dam above waste lagoon or a tailings dam with upstream construction method is subject to liquefaction under static and dynamic (cyclic) loading. Therefore, tailings dams with upstream construction method are treated as hydraulic structures of the highest risk and are not recommended in seismically active regions.

The heightening of the existing tailings storage facilities (TSF), with construction of a new tailings sand dam above the existing waste lagoon (a method similar to the upstream advancement of TSFs), is a heterogeneous geoenvironment that is subject to liquefaction under static and dy-namic (cyclic) loading and therefore they are hydraulic structures with the highest risk for stability (Petkovski L., 2022). The analysis of the stability of these heterogeneous geoenvironment con-firmed that the critical loading condition by comparing (a) the long-term static load (with the highest required reliability coefficient 1.5), (b) the short-term static load (with the lower required reliability coefficient 1.3), (c) the seismic resistance during the earthquake action (where short variations are tolerated with a safety factor of less than 1.0), and (d) incidental loads during the occurrence of liquefaction (with a required safety factor of 1.1), is precisely the occurrence of liquefaction. Therefore, we are on opinion that the occurrence of liquefaction (static and dynamic) must become obligatory loading condition for the tailings storage facilities, because the most of-ten adopted geometry and composition of the cross-section (the distribution of the local materials) which guarantees the required stability depends on the loading condition.

2 STATIC AND DYNAMIC LIQUEFACTION

The phenomenon of liquefaction occurs in saturated and loose (insufficiently compacted) sands, which are present in certain zones of the TSFs. When liquefaction occurs, regardless of whether it is static or dynamic, the structure of the particles is destroyed and the shear strength of the material rapidly decreases to steady-state strength. Static liquefaction (Petkovski L., Mitovski S., 2019) is possible in the following two cases, Figure 1: (a) with an additional external load that results in increase of shear stress, whereby point (A) in the (qp`) diagram moves 'up' to an inter-section with the failure surface and (b) with additional saturation and reduction of effective nor-mal stresses, point (A) in the (qp') diagram moves 'left' to an intersection with the collapse surface. Dynamic liquefaction (Petkovski L., Mitovski S., 2018) occurs during the action of an earthquake, where cyclic loading causes a continuous increase in pore pressure, which results in a decrease in effective stresses, whereby point (B) in the (qp`) diagram moves "left" to an intersection with the collapse surface, Figure 2.

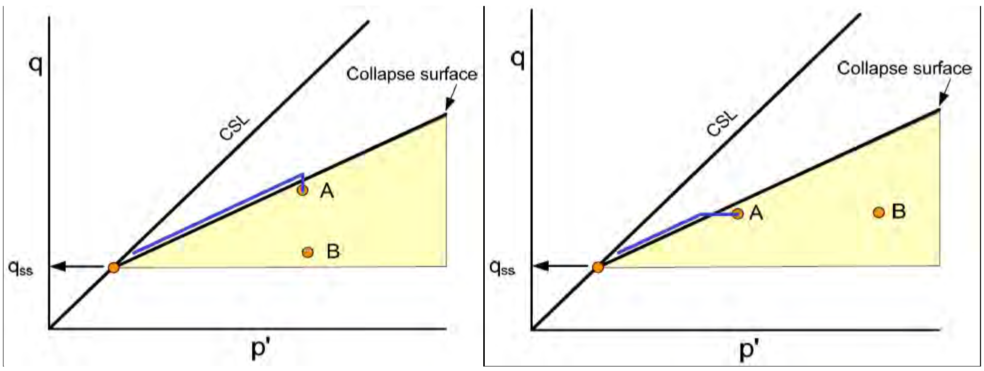

Figure 1. Effect of (a) shear stress (at the same confining stress) and (b) confining stress (at the same shear stress) on the liquefaction potential,

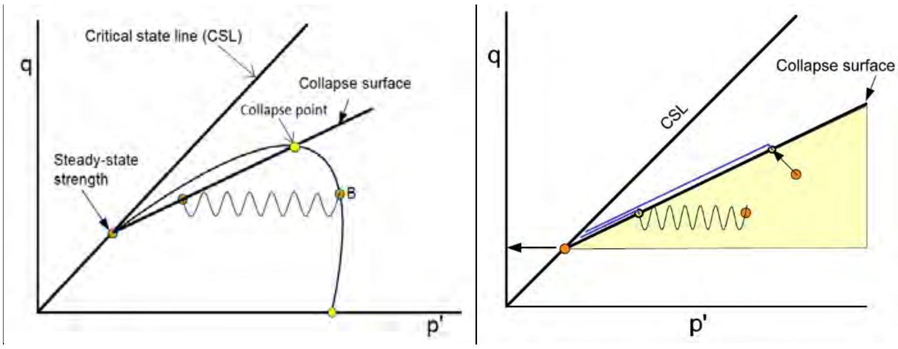

Figure 2. Cyclic stress path from point B to the collapse surface in the potentially liquefiable region

3 MODIFICATIONS TO THE HEIGHTENING OF THE 'TORANICA 1' TSF IN NORTH MACEDONIA

"Toranica" mine, K. Palanka (Bulmak) is currently operating with an ore production of approximately 320,000 t /year, and for the needs of that production, the existing TSF 'Toranica 1' is in operation. The waste lagoon was created with upstream and downstream dam, Figure 3. The upstream (diversion or retention) dam is a conventional dam (earth dam with a clay screen) with crest elevation at 977.5 masl. The downstream dam is a tailings dam constructed with the downstream method of construction by cycloned tailings sand.

The existing 'Toranica 1' TSF, so far has been heightened twice above elevation 977.5 masl. The first heightening was up to crest elevation of 990.0 masl. The retention dam was heightened by a tailings dam with a central construction method, but with a crest displaced from the conventional dam, i.e. founded on the waste lagoon, at position "A" (Figure 4). The second heightening, which is in the construction stage, was designed up to an elevation of 1,000 masl, in accordance with the technical documentation for the 'Toranica' mine TSF (Geing - Skopje, 2018). With this project, it was foreseen that the retention dam would be heightened by a tailings dam with a crest at 1,000 masl. made from cycloned sand with a central construction method, founded on the waste lagoon at position "B".

An alternative solution for the heightening of the upstream dam up to the elevation of 1,000 masl, analyzed in Annex 1 (DIPKO - Skopje, 2022), Figure 5, is with a cyclone location near "A", apropos moved upstream by 47.25 m compared to "B". By comparing variants "B" (2018) and "A" (2022), at same level of technical investigation of the stability, with limit equilibrium method and shear strength in undrained conditions in the existing waste lagoon, it was confirmed that the variant " A" poses higher degree of stability.

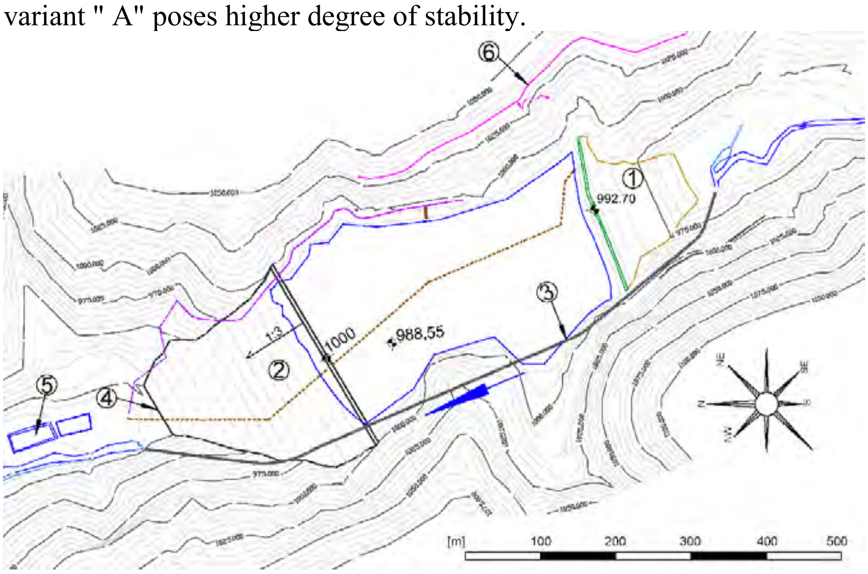

Figure 3. Layout of 'Toranica 1' TSF, according to the geodetic survey from September 2023. (1) upstream or retention or diversion dam, (2) downstream or tailings dam, (3) diversion tunnel, (4) gabion wall to protect the exit structure of the tunnel, (5) sedimentation tanks for drained and treated water, (6) pulpline.

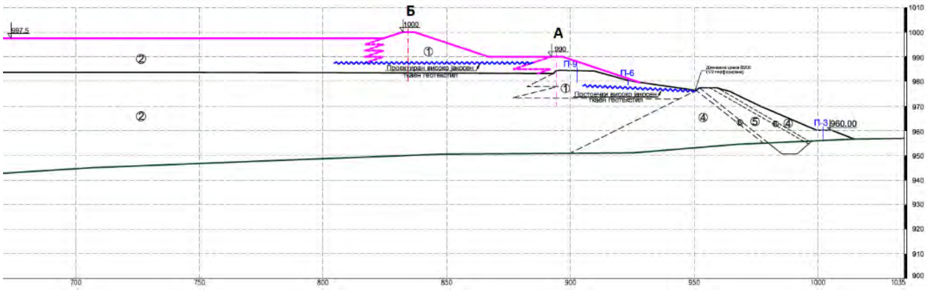

Figure 4. Schematic display of the heightening of the upstream (retention) dam at tailings dam ‘Toranica’, according to annex 3 of Basic Design from 2018-09-12.

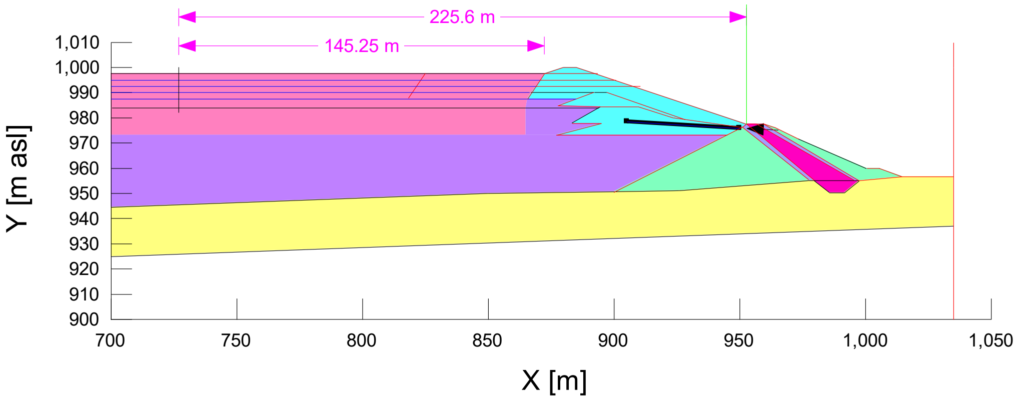

Figure 5 Model for heightening of the upstream (retention) dam of the tailings dam Toranica, according to Annex 1 from 2022-08-30.

In October 2023, the heightening of the upstream (retention) dam (Figure 6) till elevation 1,000.0 masl was carried out according to Annex 2 (DIPKO - Skopje , 2023), prepared by using data from SPT and CPT field geotechnical investigations (DIPKO – Skopje, 2023.03.16). With the dynamic analysis in Annex 2 for the solution of the cross-section according to Annex 1, a stability factor lower than 1.0 was obtained for the post-earthquake condition with the occurrence of liquefaction in the waste lagoon. A variant was adopted with a minimum amount of embedded mine rockfill and which provides a stability factor (F) at least as much as is permitted for the condition after an earthquake at occurrence of liquefaction (F_{per}), that is value of $F=1.152>F_{per}=1.1$. That form of "supported drainage" has the following dimensions: a berm width of 4.0 m and a height of 12 m, that is, from the crest elevation of the original diversion dam at 977.5 masl (with a crown width of 6.9 m) till elevation 990 masl.

Taking into account the long period for obtaining the Approval for the construction of the new ‘Toranica 2’ TSF, (downstream of ‘Toranica 1’, for which geotechnical investigations and a reviewed Basic Design have been prepared), which due to numerous administrative bureaucratic difficulties can be extended to 4-5 years, the Client ‘Bulmak, Probishtip’ approved the continuation of the exploitation of the existing ‘Toranica 1’, with a new heightening at 1,005 masl.

By the heightening till 1,000 masl with the central method in position "A" was exhausted the stability of the retention dam (Annex 2) and therefore it was adopted that the heightening from 1,000 to 1,005 masl should be made with progression in the opposite direction from the waste lagoon (toward the aerial slope of the retention dam). For this purpose, the inclined layers of tailings sand (with slope V:H=1:3) should be supported on an widened crest of the retention dam (earthrock) at elevation of 977.5 masl, Figure 7. The modified geometry of the upstream dam in the preliminary analysis (compared with Annex 2) made according to the perception and concept of the technical feasibility of heightening by 5.0 m at the ‘Toranica 1’ TSF (HEI - Skopje, 2023) was obtained with a slope of tailings sand of V:H=1:3 , a berm at an elevation of 977.5 masl wide 3.0 m and a slope of alluvium ballast V:H=1:2.3. Backfilling with gravel mix (alluvium) at a height of 977.5 - 956.6 = 20.9 m and variable width, filled in horizontal layers of 30 cm and with moderate compaction, should be carried out before disposal on the downstream slope of tailings sand with a slope of V:H=1:3, higher from the heightening at elevation of 1,000.0 masl.

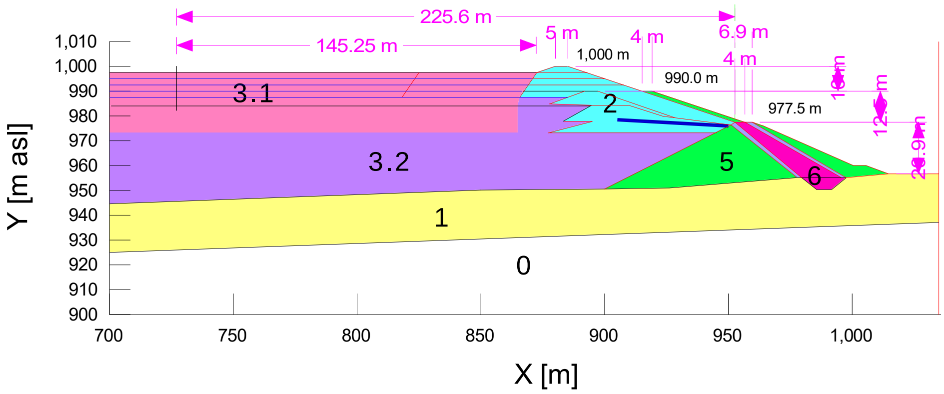

Figure 6. Model for heightening of the upstream dam up to 1,000 masl, according to Annex 2, 2023.07.03, 0 – bedrock, boundary seepage and deformable condition, 1 - gravelly mixture, alluvium at the base under the dam, 2 – cycloned tailings sand, dam, 3 - tailings mud, waste lagoon (3.1 shallow zone and 3.2 deep zone), 5 - rock, support body of retention dam, 6 - clay, inclined core of retention dam, 7 - sand, filter transition zones of retention dam.

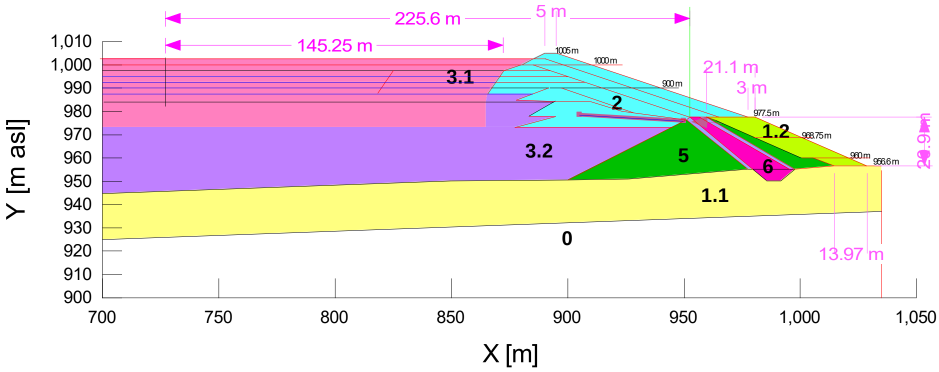

Figure 7. Modified geometry (compared with Annex 2) of the aerial slope of the upstream (retention) dam with a crest at 1.005 masl, 0 – bedrock, boundary seepage and deformable condition, 1.1 - gravelly mixture, alluvium in the base below the dam, 1.2 - gravelly mixture, fill above the aerial slope of the earth-rock dam, 2 – cycloned tailings sand, dam, 3 - tailings mud, sedimentary lake (3.1 shallow zone and 3.2 deep zone), 5 - stone, retaining body of retention dam, 6 - clay, inclined core of retention dam, 7 - sand, filter transition zones of retention dam .

4 STATIC ANALYSIS OF THE HEIGHTENING OF THE UPSTREAM DAM OF THE ‘TORANICA 1’ TSF UP TO 1,005 MASL

The structural (static, seepage and dynamic) analysis of the heightening of the upstream (diversion) dam up to 1.005 masl at the ‘Toranica 1’ TSF was made according to the latest recommendations of ICOLD, i.e. with one mathematical model for different phases of the loading, where each subsequent phase is with initial state of stresses determined by the previous stage. The adoption of the physical, mechanical, strength, deformable and water-permeable characteristics of the materials is based on the large number of field and laboratory tests, above all in the past period for the ‘Toranica 1’ TSF (Geing - Skopje, 2018), but also by comparing the sizes for the new ‘Toranica 2’ TSF (Technique 20 - Skopje, 2022).

To determine the values for the undrained shear strength of tailing mud in static conditions Su(yield)/σ`v and in liquefaction conditions Su(liq)/σ`v , which are determined by in situ SPT and CPT, data from the latest field geotechnical investigations were used (DIPKO - Skopje, 2023). The field investigations consisted of two boreholes at a distance from the upstream edge of the original conventional retention dam (with a crest level at 977.5 masl) at 55.6 m ID-1 and 72.5 m ID-2 to a maximum depth of approximately 40 m, at the maximum cross-section (approximately in the middle of the river bed). Two series of tests of standard (dynamic) penetration (SPT) and one test of conical (static) penetration with measurement of pore pressure (CPT) were carried out in the boreholes in ID-1. Liquefaction potential was estimated in the borehole ID-1, with the SPT, at a depth of about 16.1 m, and the lowest strength parameters were obtained approximately in that zone with the CPT .

With the CPT results in ID-1, for the critical depth of 15 to 25 m, CPT values were estimated and using expressions from the technical literature for the calculation of undrained shear strength (Campanella, R. G., Gillespie, D., and Robertson, P. K. 1982), (Campanella, R. G., et al. 1985), (Olson, S.M., and Stark, T.D. 2003), (Robertson, P.K. 2010), (Robertson, P.K. 2016), (Robertson, P.K., 2020), the values for Su(yield)/σ`v and Su(liq)/σ`v are determined. For the further analyses, the following values are adopted Su(yield)/σ`v = 0.21 and Su(liq)/σ`v = 0.04.

The initial state of stresses before the beginning of the heightening is determined by approximating the pore pressure distribution according to the measured data with piezometers (Figure 8), 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.

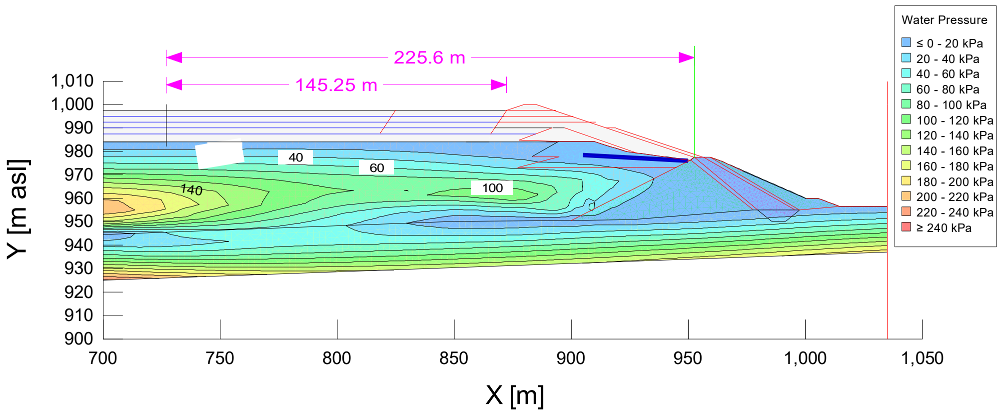

Figure 8. Approximated initial state for pore pressure in the tailings dam.

With the initial stress state of the waste lagoon at an elevation of 984 masl, the heightening was simulated in 7 load stages, for the following elevations in the lagoon: 987.5, 990.0, 992.5, 995.0, 997.5, 1,000.0 and 1,002.5 masl, so that the crest of the dam from cycloned sand is always 2.5 m higher than the waste lagoon. Each stage (layer) of the waste lagoon and sand dam with a height of 2.5 m has a duration of 180 days and was calculated by consolidation analysis in 10 load increments with an exponential increase, because the dissipation of excess pore pressure is most intense in the initial period. The construction of the alluvium embankment along the aerial slope of the retention dam begins after reaching the crown elevation of the sand dam at 1,000.0 masl The alluvium embankment is simulated in 3 load cases up to elevations 960.0, 968.75 and 977.5 masl with a duration of 15, 30 and 30 days each (or a total of 75 days), with consolidation analysis in 5 load increments with exponential growth.

At the end of each stage in the construction phase are determined the cumulative values of the horizontal and vertical displacements (Figures 9 and 10) and the effective normal vertical stresses (Figure 11), which should be compared with the measured quantities from the technical observation.

Final for stage no. 7 of the construction phase of the heightening are checked: the critical sliding surfaces (with minimum stability factor), for the first load increment (immediately after applying the load of 2.5 m), Figure 12, and for the final load increment (with dissipation of the part of the excess pore pressure after 180 days) and at action of earthquake, by applying the pseudostatic method, Figure 13, with seismicity coefficient Kcx = 0.10 and Kcy = -0.07.

The development and dissipation of consolidation pore pressure at an elevation of 965 masl, for a distance X of the model from 880 m to 900 m, Figure 14, i.e. in the critical zone of the waste lagoon, under the cycloned sand dam heightened to 1,005 masl, is key to its stability. This dependency was simulated in 7 stages during the construction of the waste lagoon after 180 days, i.e. in a period of 7*180 = 1,260 days and 75 days for the construction of the alluvium embankment on the aerial side of the earth - rock dam, or for a total period of 1,335 days (115,344,000 s or 3.66 years) .

The distribution of the coefficient q/p' [-], or the ratio of the tangential resistance to the mean effective normal stresses, for the initial condition indicates high values in certain zones in the tailings dam. Zones in the waste lagoon with values (q/p') > (0.42-0.44) are located above the "collapse surface" and are liquefied (Figure 15). As follows, the critical collapse surface is shown for the slope of the retention dam (Figure 16) in the pre-earthquake stage, with shear strength in liquefied zones (in case of static liquefaction).

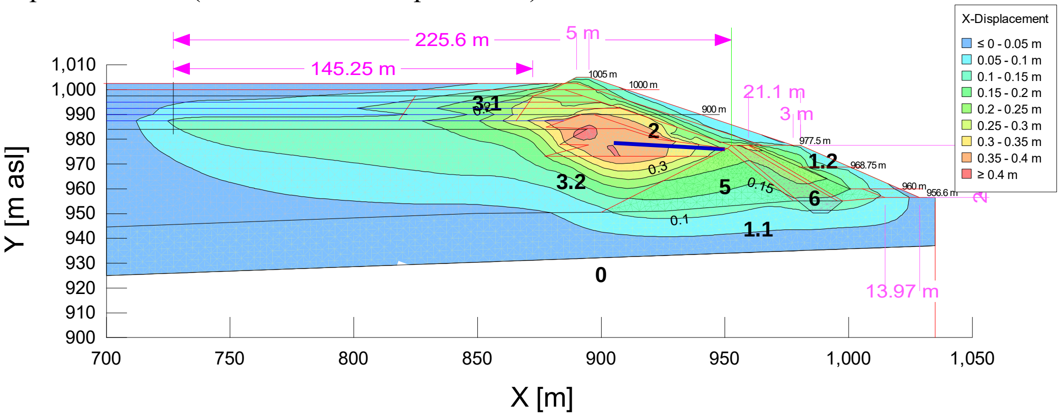

Figure 9. Isolines of horizontal displacements, waste lagoon at elevation of 1,002.5 masl.

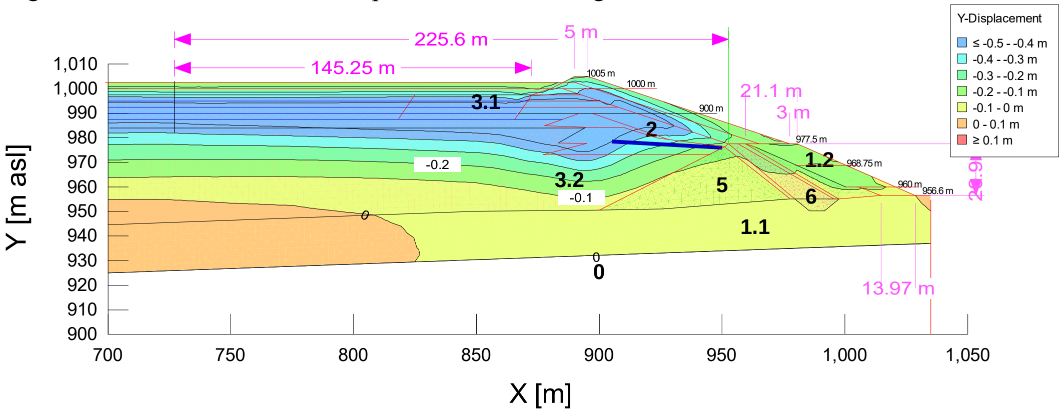

Figure 10. Isolines of vertical displacements, waste lagoon at elevation of 1,002.5 masl.

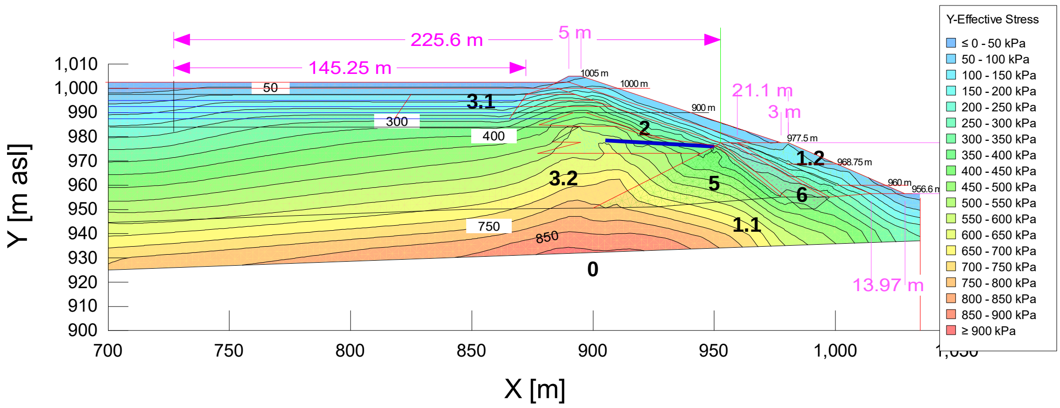

Figure 11. Isolines of vertical effective normal stresses, waste lagoon at elevation of 1,002.5 masl

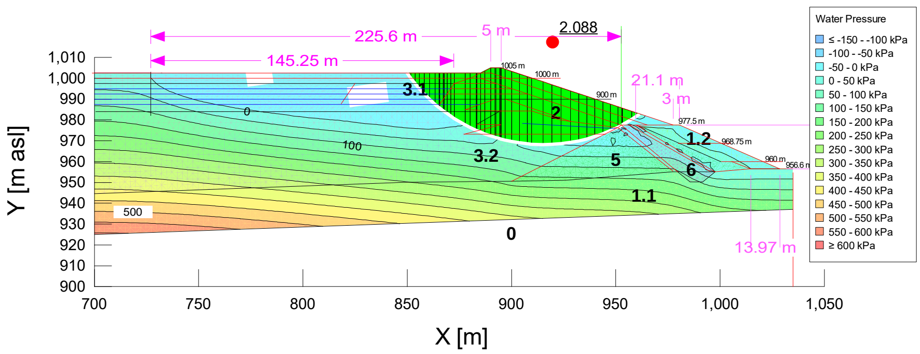

Figure 12. Critical collapse surface in the first load increment immediately after applying of layer of 2.5 m, waste lagoon at elevation of 1,002.5 masl.

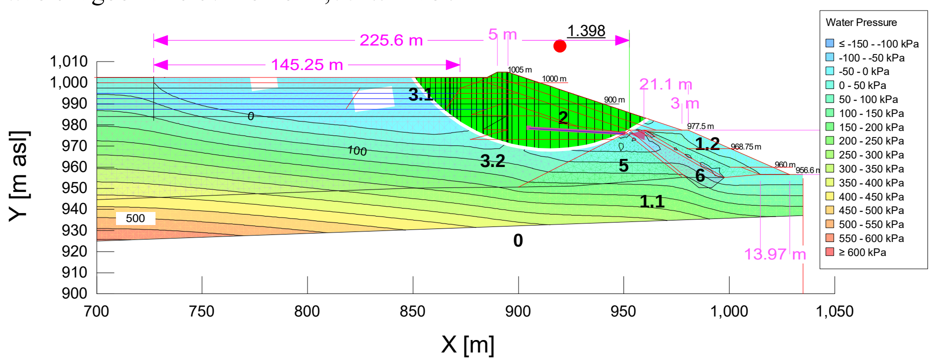

Figure 13. Critical collapse surface in the last load increment after 180 days and at action of earthquake (pseudostatic), waste lagoon at elevation of 1,002.5 masl.

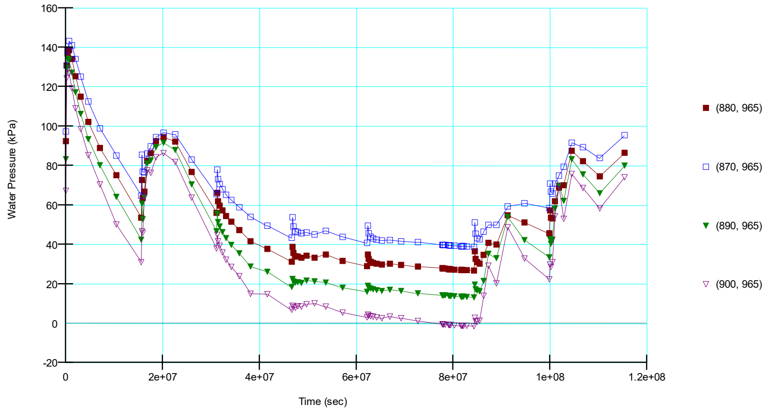

Figure 14. Development (increase) and dissipation (decrease) of the consolidation pore pressure in the waste lagoon at elevation of 965 masl, in the zone below the cyclone sand heightening.

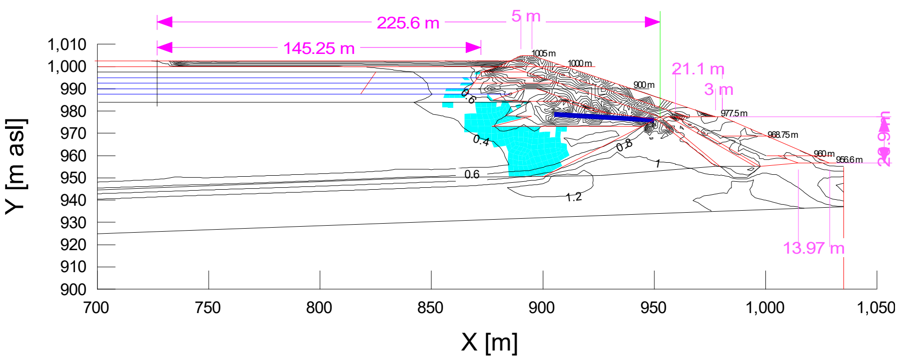

Figure 15. Distribution of the coefficient q/p' [-] with liquefied zone, for the initial (pre-earthquake) state of stresses, when the tailings mud is subjected to liquefaction.

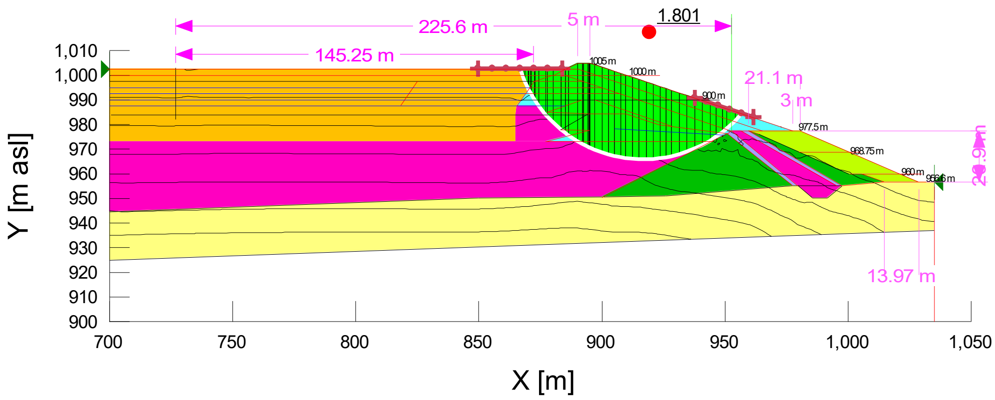

Figure 16. Critical collapse surface in pre-earthquake stage, with shear strength in liquefied zones (static liquefaction).

5 CONCLUSIONS

With the initial stress state of the tailing dam for waste lagoon at elevation of 984 masl, the heightening was simulated in 7 load stages, for the following elevations in the lagoon: 987.5, 990.0, 992.5, 995.0, 997.5, 1,000.0 and 1,002.5 masl, so that the crest of the dam from cycloned sand is always 2.5 m higher than the waste lagoon. Each stage has a duration of 180 days and is simulated in 10 load increments with an exponential increase, because the dissipation of consolidation pore pressure is most intense in the initial period. The construction of the alluvium embankment along the aerial slope of the retention dam begins after reaching the crest elevation of the sand dam at 1,000.0 masl The alluvium embankment is simulated in 3 load cases up to elevations 960.0, 968.75 and 977.5 masl with duration of 15, 30 and 30 days each (or a total of 75 days), with consolidation analysis in 5 load increments with exponential growth.

The displacements (horizontal and vertical) are determined for all 7 load stages of the tailings sand heightening, which should be compared with those measured during the t4echnical monitoring in construction stage, in order to draw out valid conclusions about the regular behavior of the geoenvironment. The development and dissipation of the consolidation pore pressure is determined at elevation of 965 masl, for X of the model from 880 m to 900 m, i.e. in the critical zone of the waste lagoon, under the cycloned sand dam heightened to an elevation of 1,005 masl, which should be compared with the measured piezometric pressures during the technical monitoring in construction stage. By analyzing the consolidation of the ‘Toranica’ waste lagoon with the heightening up to 1,005 masl, for two different scenarios in the post-exploitation period (according to the level of drying out), in the first year primary settlements in the crest of 8 to 12 cm can be expected. Therefore, a heightening of the crest at 1.005 masl was adopted for a value of 20 cm in the central cross-section, with a linear decrease towards the banks to a zero value.

The general conclusion that with the heightening of the upstream (retention) dam of the ‘Toranica 1’ waste lagoon, according to the adopted geometry and composition of the local materials, satisfactory static stability is provided, according to the valid design regulations, is based on the following facts.

For all 7 load stages during construction, the stability against sliding of the slope was checked, for two cases: (a) immediately after applying a new layer of 2.5 m, where temporary stability with F_{doz}=1.3 was satisfied and (a) after 180 days from the application on the new layer, where permanent stability is satisfied with F_{per} = 1.5. At the same time, the pseudo-static reliability of the heightening of the crest at 1.005 masl with F_{per} = 1.1 is satisfied.

For the critical collapse surface for the downstream slope in the pre-earthquake stage, with shear strength in liquefied zones (in case of static liquefaction conditions), a high stability factor of 1.801 is obtained, significantly higher even than that allowed for permanent stability F_{per}=1.5.

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