7th Meeting of the EWG

International Symposium
on Dams and Earthquakes

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Athens, Greece • September 12-13, 2024

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- *Earthquake hazard parameters for dam safety evaluation.*
- *Measurement of seismic and post-seismic response of concrete and embankment/tailings dams.*
- *Experimental behavior and modeling of dam materials under cyclic loading.*
- *Seismic performance of concrete dams and their impacted area. Case histories, analysis & validation, design.*
- *Seismic performance of embankment/tailings dams and their impacted area. Case histories, analysis & validation, design.*
- *Earthquake safety evaluation of safety-critical dam elements.*

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Seismic resistance assessment of a diverting rock-earth dam heightened with tailings dam

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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 dynamic (cyclic) loading and therefore they are the civil engineering structures with the highest stability risk. This heightening is characterized by detailed geotechnical in-situ investigations, sophisticated structural analyses (static, non-steady seepage, and dynamic), and necessary modification of the geometry of the embankment. That is illustrated by the results of the dynamic analysis and seismic resistance assessment of a heightening of the existing upstream combined diverting dam and modification of the previous rockfill dam with clay core, with tailings sandy dam above the waste lagoon of the tailings storage facility Toranica, Kriva Palanka, Republic of North Macedonia.*

Keyword: *Tailings dam, Heightening, Seismic resistance*

1 HEIGHTENING OF TAILINGS DAMS WITH TAILINGS SAND ABOVE EXISITNG LAGOONS

In case of tailings dams the lowest safety is obtained by upstream method of construction. In such case, for each subsequent stage, the dam crest is displaced upstream apropos the sandy dams are founded on the deposited tailings silt. The heterogeneous medium – tailings dam over waste lagoon or tailings dam with upstream method of construction is subjected to liquefaction under static and dynamic (cyclic) loading. Therefore, the heightening of the tailings facility with tailings dams over waste lagoons are treated as hydraulic structures of highest risk and are not recommended in seismic active regions.

Logical question arises – from where comes the need of the mining companies to initiate solutions with heightening over existing waste lagoons? It is obvious that they are embankments structures with highest risk and for confirmation of their safety are necessary detail geotechnical investigations and sophisticated structural (static, seepage, dynamic) analysis apropos high financial investment. The explanation, in our opinion, is as follows (Petkovski, 2022.11). On one hand, the space for survival, development and growth of mining companies, essential for the existence of the population in certain regions (which rely on the mining complex), due to the imposition of increasingly strict environmental and sociological criteria, is becoming more and more limited. On 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

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companies is prolonged in a long-term exhausting administrative process with the highly uncertain outcome. Therefore, mining companies are more and more often opting for solutions for the riskiest hydraulic engineering facilities, i.e. heightening with cycloned sand over the existing waste lagoons of water-saturated tailings mud.

The heightening of the existing tailings dams, with the construction of a new tailings sand dam over existing waste lagoon (a method similar to the upstream advancement of tailings dam facilities), is a heterogeneous geo-environment that is subjected to liquefaction under static and dynamic (cyclic) loading and therefore they are hydraulic engineering structures with greatest safety risk. The analysis of the stability of these heterogeneous geo-environments confirmed that the critical loading state by comparing: (a) the long-term static (with the highest required safety coefficient 1.5), (b) the short-term static (with the lower required safety coefficient 1.3), (c) the seismic resistance during earthquake action (where short excursions are tolerated with a safety factor 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 believe that the occurrence of liquefaction (static and dynamic) must become a mandatory loading condition of the tailings dams, because the commonly adopted geometry and composition of the cross-section (the arrangement of local materials) which guarantees the required stability depends on this loading condition.

2 THE LIQUEFACTION PHENOMENA

The liquefaction phenomena occur in water-saturated and loose (insufficiently compacted) sands, which are represented in certain zones of the hydraulic tailings dams. When liquefaction occurs, regardless of whether it is static or dynamic, the structure of the granules is destroyed and the shear strength of the material rapidly decreases to steady-state strength. In the context of Critical state line (CSL) and Collapse surface (CS) in the (q-p`) stress space we distinguish static and dynamic liquefaction, Figure 1. Where $q = (\sigma_1 - \sigma_3)$ is a deviator stress and represents the shear of the soil material and $p' = (\sigma'_1 + \sigma'_2 + \sigma'_3) / 3$ is mean effective stress, which is defined in terms of effective principal stresses. Static liquefaction (Petkovski L., Mitovski S., 2019.05) is possible in the following two cases: (a) with additional external loading causing an increase in shear stress, and (b) with additional water saturation and reduction of effective normal stresses. Dynamic liquefaction (Petkovski L., Mitovski S., 2018.07) occurs during the action of an earthquake, where cyclic loading causes a continuous increase in pore pressure, which conditions a decrease in effective stresses.

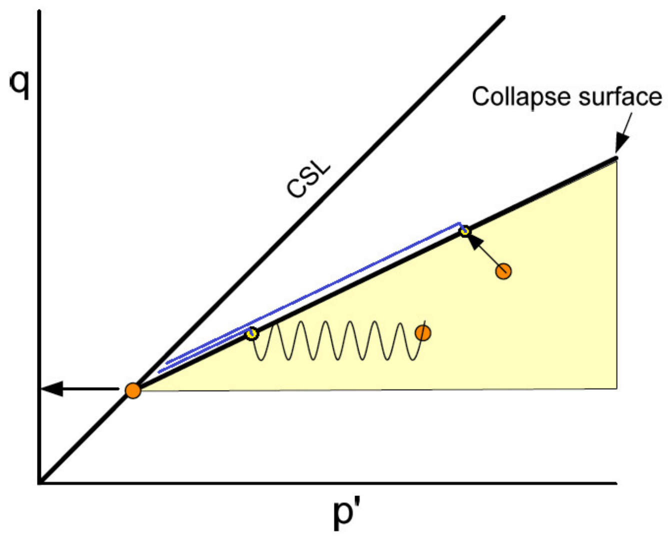

Figure 1: *Static and cyclic stress path to the collapse surface in the potentially liquefiable region (yellow shaded region).*

3 PARAMETERS OF THE TAILINGS DAM FACILITY TORANICA 1 IN N. MACEDONIA

"Toranica" mine, K. Palanka (Bulmak) currently operates with an ore production of about 320,000 t/year, and for the needs of that production, the existing tailings dam facility Toranica 1 is in operation. The waste lagoon of the tailings dam is created with upstream (upward) and downstream (downward) dam, Figure 2. The upstream (diversion or retention) dam is a conventional dam (earth fill with a clay facing), with crest elevation at 977.5 masl (meters above sea level). The downstream dam is a tailings dam with a downstream construction of cycloned tailings sand.

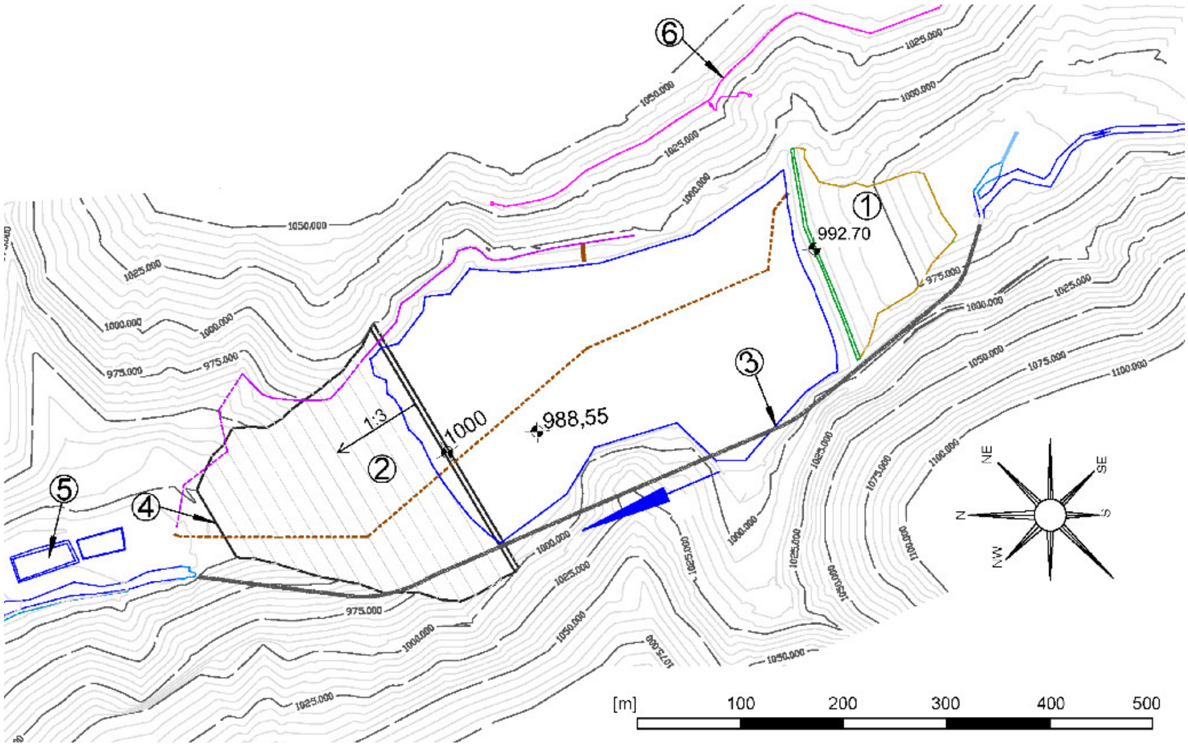

Figure 2: *Layout of 'Toranica 1' TSF, according to the geodetic survey from September 2023. (1) upstream or retention or diversion dam, (2) downstream or tailings dam, (3) diversion tunnel, (4) gabion wall to protect the exit structure of the tunnel, (5) sedimentation tanks for drained and treated water,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

The existing tailings dam Toranica 1 so far has been heightened twice over 977.5 masl. The first heightening was to crest elevation of 990.0 masl. The retention dam was heightened by a tailings dam with a central method of construction, but with a displaced crest from the conventional dam towards the waste lagoon i.e. founded on tailings mud. The second heightening to an elevation of 1,000.0 masl is carried out according to a design with proven dynamic stability using data from SPT and CPT field geotechnical surveys. In that design, a variant with a minimal amount of embedded mine stone in the form of supported drainage was adopted, which provides a stability factor (F) at least as much as is allowed for the condition after an earthquake in the case of liquefaction (Fper), i.e. with a value of F = 1.152 > Fper = 1.1 (permitted coefficient of safety in extreme conditions). The supported drainage has the following dimensions: a width of the berm of 4.0 m and a height of 12 m apropos from the crest elevation original diversion dam at 977.5 masl (with a crest width of 6.9 m) up to elevation of 990 masl, Figure 3.

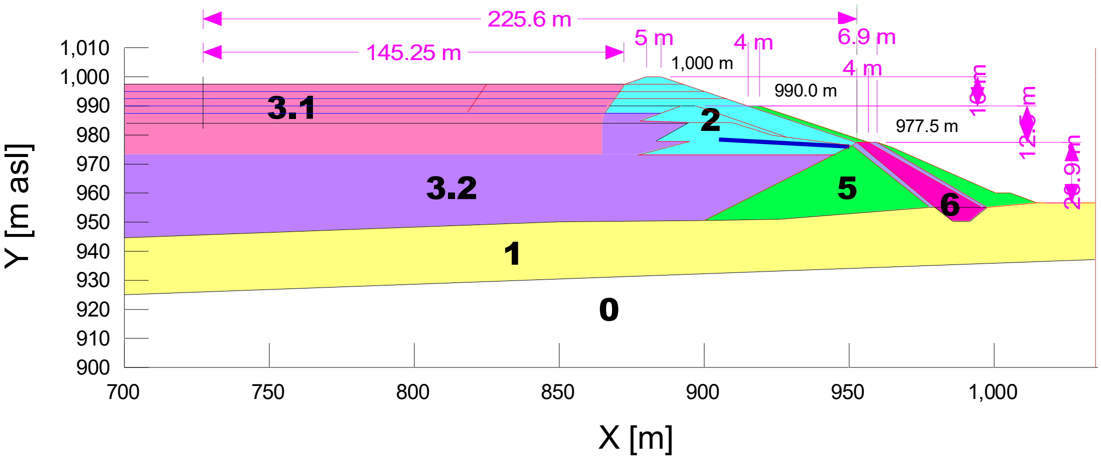

Figure 3: *Model of the heightening to **1,000** masl of the upstream (retention) dam Toranica_1, with confirmed post-earthquake stability. 0 – bedrock, boundary seepage and deformable condition, 1 - gravelly mixture, alluvium at the base un-der the dam, 2 – cycloned tailings sand, dam, 3 - tailings 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.*

By the heightening till 1,000 masl with the central method was exhausted the stability of the retention dam 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 widened crest of the retention dam (earth rock) at elevation of 977.5 masl, Figure 4. The modified geometry of the upstream dam was obtained with a slope of tailings sand of V:H=1:3, a berm at the 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 50 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.

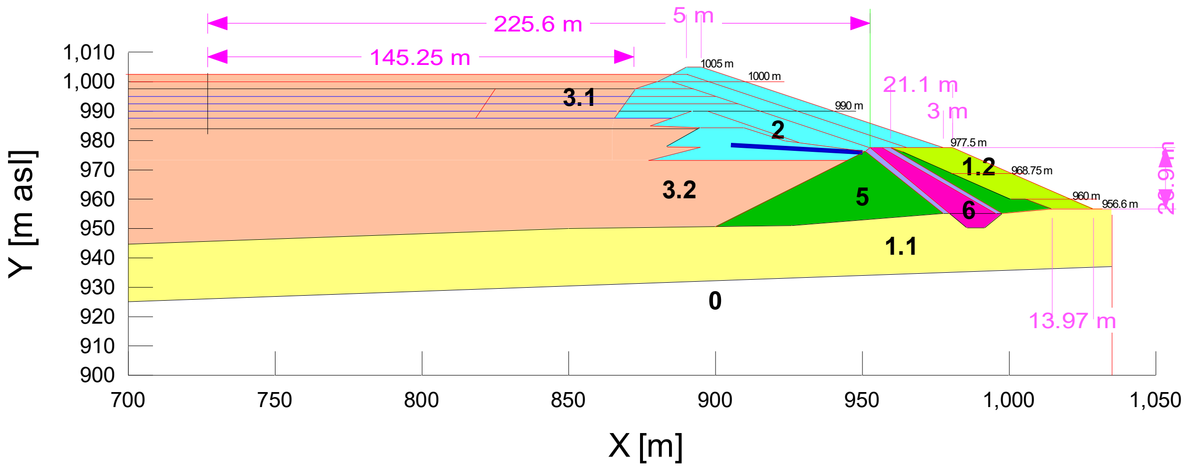

Figure 4: *Model of the heightening to **1,005** masl of the upstream (retention) dam Toranica_1, 0 – bedrock, boundary seepage and deformable condition, 1.1 - gravelly mixture, alluvium in the base below the dam, 1.2 - gravelly mixture, fill above the aerial slope of the earth-rock dam, 2 – cycloned 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.*

In the remaining text of the paper, an overview of the key settings and conclusions from the structural (static, seepage and dynamic) analysis of the heightening (overtopping) of the upstream (diversion) dam from elevation 997.5 to 1,005.0 masl of the tailings storage facility (TSF) Toranica_1 is given.

4 DYNAMIC ANALYSIS OF THE HEIGHTENING OF THE UPSTREAM DAM TORANICA 1 TILL ELEVATION 1,005 MASL

The structural (static, filtration and dynamic) analysis of the heightening of the upstream (diversion) dam up to 1.005 masl at the tailings dam Toranica 1 was made according to the latest recommendations of ICOLD, i.e. with one mathematical model for different loading stages, where each subsequent stage 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, primarily in the past period for the tailings dam Toranica_1, but also with a comparison of the values for the new tailings dam Toranica_2.

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 were determined by in-situ SPT and CPT, data from the latest field geotechnical investigations (DIPKO - Skopje, 2023.03.16) were used. The field investigations consisted of boring of two boreholes at a distance from the upstream edge of the original conventional retention dam (crest at elevation 977.5 masl) ID-1 at 55.6 m and ID-2 at 72.5 m to a maximum depth of about 40 m, at the maximum cross-section (approximately in the middle of the river bed). Two series of standard (dynamic) penetration tests (SRT) and one cone (static) penetration test with pore pressure measurement (CPT) were carried out in the boreholes in ID-1. In borehole ID-1, liquefaction potential was estimated at a depth of about 16.1 m, with SPT, and the lowest strength parameters with CPT were obtained approximately in that zone.

With the CPT results in ID-1, for the critical depth of 15 to 25 m, Figure 5, values for CPT 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 of Su(yield)/$σ`_v$ and Su(liq)/$σ`_v$ were determined. For further analysis, the following values Su(yield)/$σ`_v$ = 0.21 and Su(liq)/$σ`_v$ = 0.04 were adopted.

The values of the residual strength of liquefied local materials Su(liq)/$σ'_y$, were determined using the data of the effective vertical stresses, and the values systematized in Table 1 were adopted.

Table 1. *Parameters of consolidated undrained shear strength.*

		Static	Initial	Dynamic	Dynamic
φ_1	zone	Su/$σ'_y$	$σ'_y$	Su(liq)/$σ'_y$	Su(liq)
o			kPa		kPa
10	shallow lagoon	0.19	300	0.04	12
10	deep lagoon	0.21	600	0.04	24

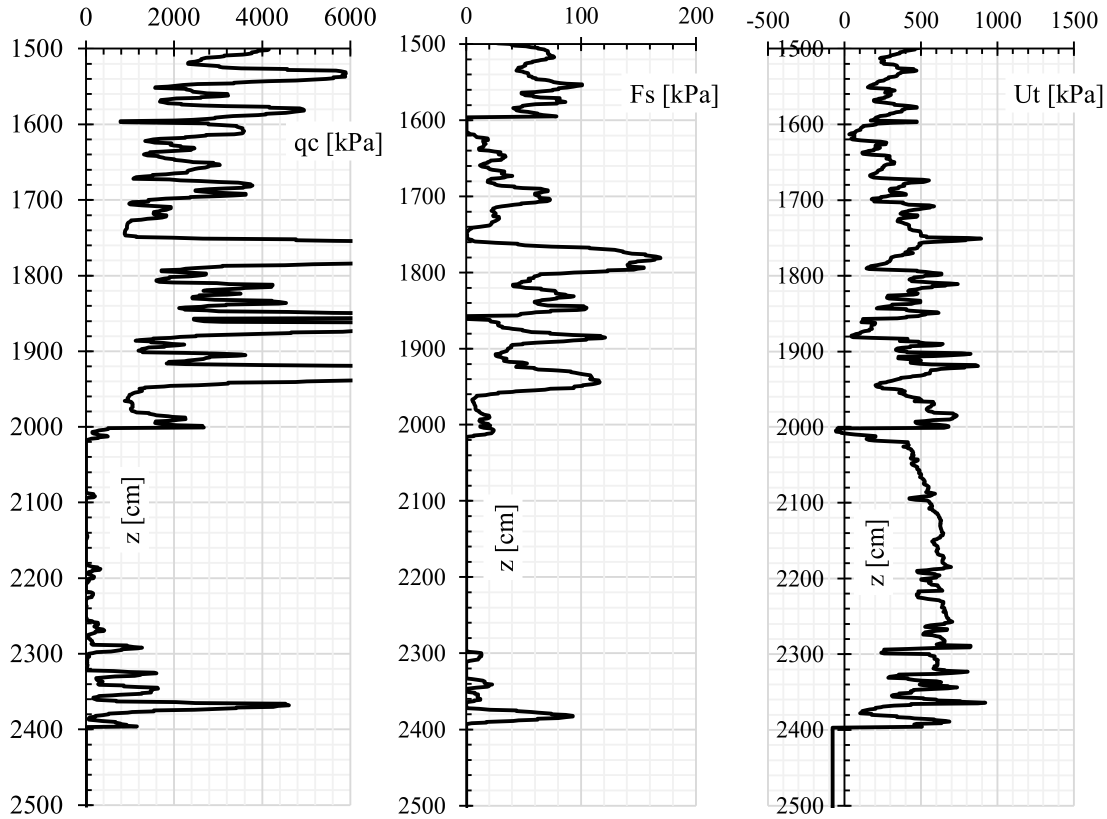

Figure 5: *(1) qc - CPT cone resistance, (2) Fs - CPT sleeve friction, (3) Ut - Total pore pressure during penetration, measured behind the tip.*

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, with the type of "Insitu" analysis, thus simulating the initial state of total stresses (initial state for the next stage of loading) and effective stresses.

With the initial stress state of the tailings dam for the waste lagoon at an elevation of 984 masl, 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 dam crest of the 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 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 a duration of 15, 30 and 30 days each (or a total of 75 days), with consolidation analysis in 5 load increments with exponential raise. With the described approach, the pre-earthquake state of stresses was obtained, Figure 6, for which a dynamic analysis was carried out.

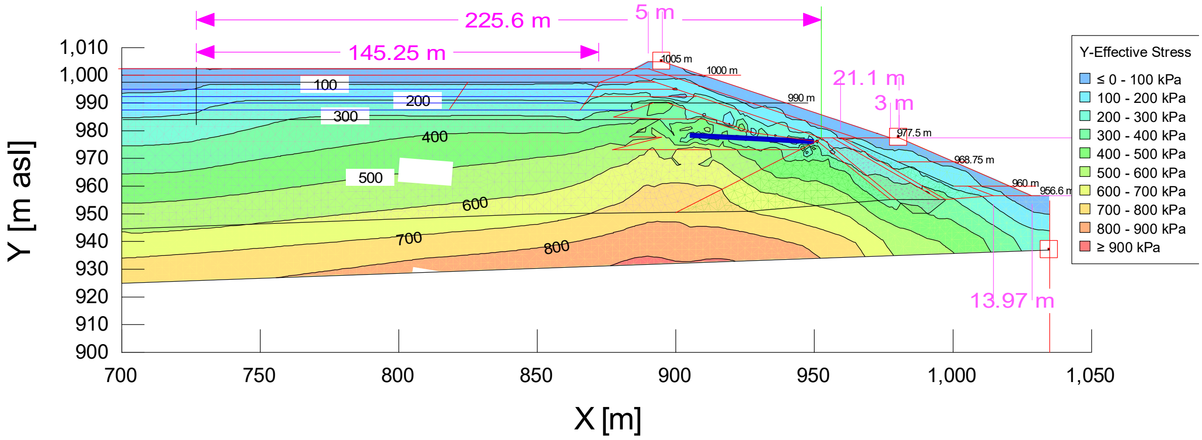

Figure 6: *Isolines of vertical effective normal stresses, waste lagoon at elevation 1,002.5 masl and dam at elevation 1005.0 masl, with history points: (2) at 937 m, (71) at 1005 m and (74) at 977.5 m*

The selection of the parameters of the design earthquakes and the adoption of the dynamic parameters are taken over from a appropriate seismological data base (IZIIS - Skopje, 2020.10). The usual procedure for analyzing the dynamic response of tailings dams with waste lagoons is to be carried out with at least three different accelerograms, for two levels of seismic excitation: (1) Operating Basis Earthquake (OBE) and (2) Safety Evaluation Earthquake (SEE), Figure 7.

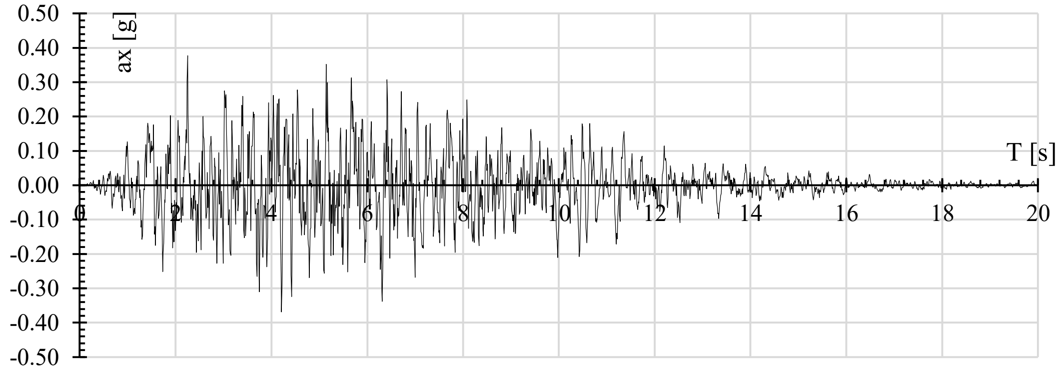

Figure 7: *Time history (accelerogram) of horizontal component of the accelerations for SEE earthquake T-10.000-1 for t3 = 20 s, PGAx3 = 0.36 g (excitation), at history point (2).*

In this paper, having in mind the size and importance of the tailings storage facility Toranica_1, as well as the available dynamic material parameters, it is adopted the dynamic behavior of the dam to be determined by the application of Equivalent Linear (EL) Analysis (Geo-Slope QUAKE/W v8, 2018). The dynamic response of the geo-environment, during SEE with PGAx = 0.36 g and PGAy = 0.25 g, duration of t =20 s, with synthetic accelerogram T=10,000_1, is displayed in Figures 8 and 9. A visual control that the dynamic response is correct is the diagram of the relative horizontal displacements, Figure 10.

The permanent vertical displacement, caused by the inertial forces during the excitation, which is relevant for the assessment of the seismic resistance of the dam crest at 1.005 masl is the crest settlement equal to 65 cm, as calculated by the Dynamic Deformation (DD) method, (Geo-Slope SIGMA/W v8, 2018) Figure 11. This DD analysis is a successive non-linear redistribution of the stresses in a geo-medium discretized by finite elements (FE). The analysis calculates deformations caused by forces in nodes, that are calculated by the incremental stresses in the elements. Thus, by application of a non-linear soil model, for each time step of the dynamic response of the structure a new state of total stresses and pore pressures is obtained. The differences of the effective stresses in two successive time steps give the incremental forces, which result in deformations, in accordance with the chosen constitutive stress – strain law. So, for each loading case during the dam's dynamic response, both elastic and plastic strains are produced. If the dynamic inertial forces cause plastic strains, then in the geo-medium permanent deformations will occur. The permanent displacements, at any point in the dam and at end of the seismic excitation, are a cumulative sum of the plastic deformations.

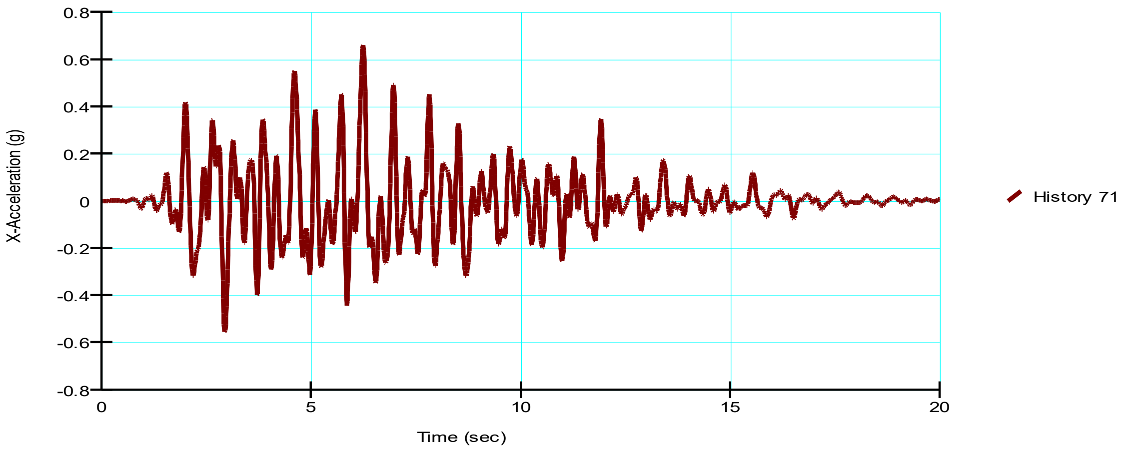

Figure 8: *Absolute accelerations a[g] ÷ t[s] in horizontal direction, at crest of retention dam Toranica „1" with heightening at 1,005 masl (response), at history point (71).*

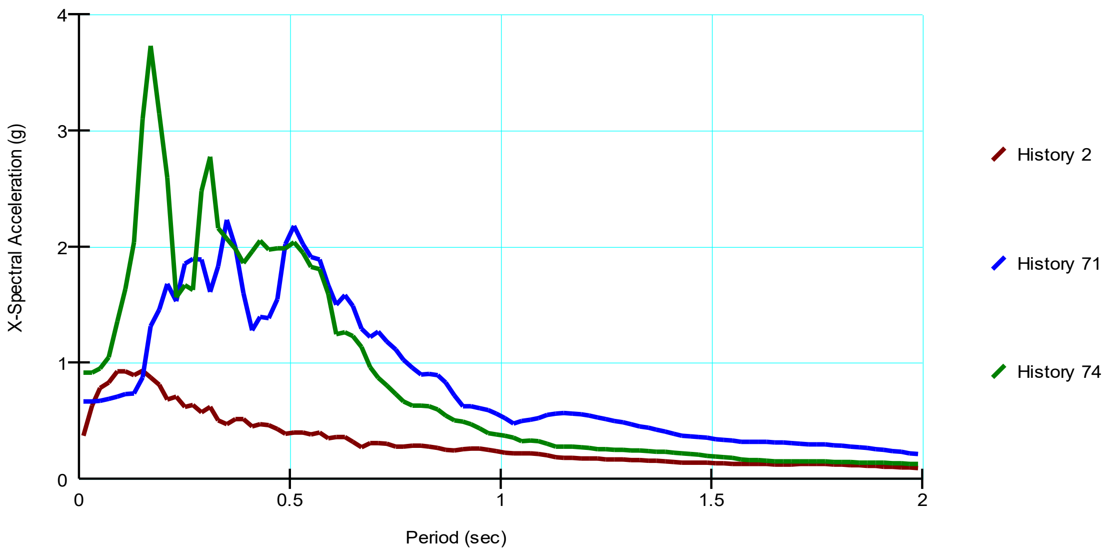

Figure 9: *Response spectrum of accelerations Sa [g] ÷ T [s] for DR = 0.05, in the rock foundation "2" (excitation) and in the berm of the embankment of the retention dam "74" at 977.5 mv (response) and in the crest of the heightened dam "71" at 1.005 masl (response).*

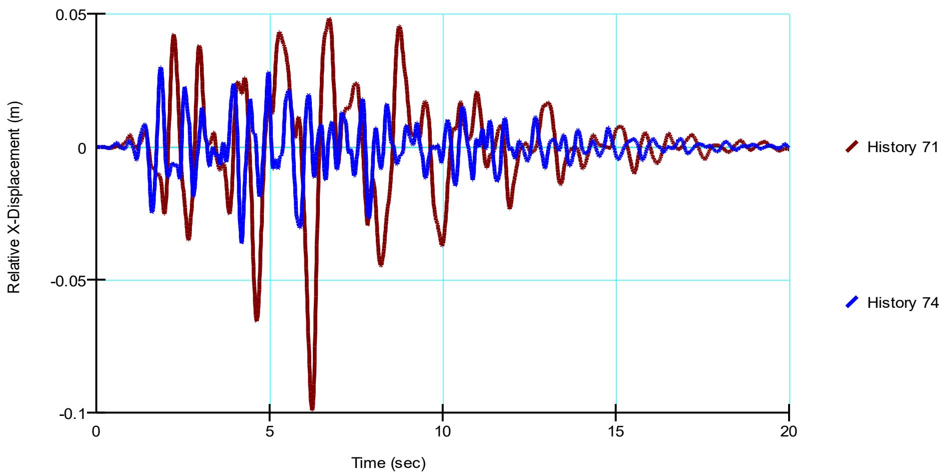

Figure 10: *Relative displacements, horizontal x[m] ÷ t[s], in the berm of the embankment of retention dam "74" at 977.5 masl (response) and in the crest of the heightened retention dam "71" at 1.005 masl (response).*

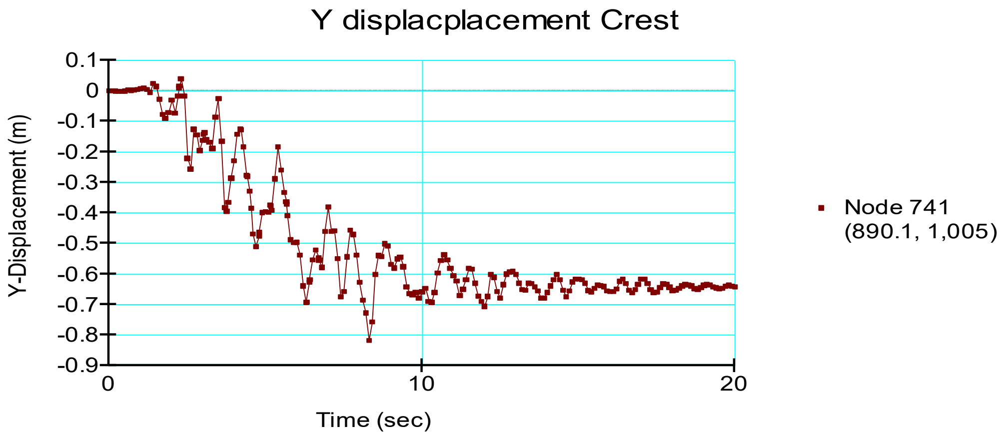

Figure 11: *Permanent vertical settlements of 65 cm, determined by the DD method in the upstream edge of the dam crest at elevation of 1.005 masl, at history point (71) or FE mesh node 741*

During the earthquake, there is an increase in the pore pressure, which creates a liquefaction zone after the earthquake action. At the q/p′ stress state, the q/p′ ratio is the deviator stress divided by the mean effective stress and the liquefied zone is where the q/p′ ratio is between the critical state line (CSL) and the collapse surface (CS), Figure 12.

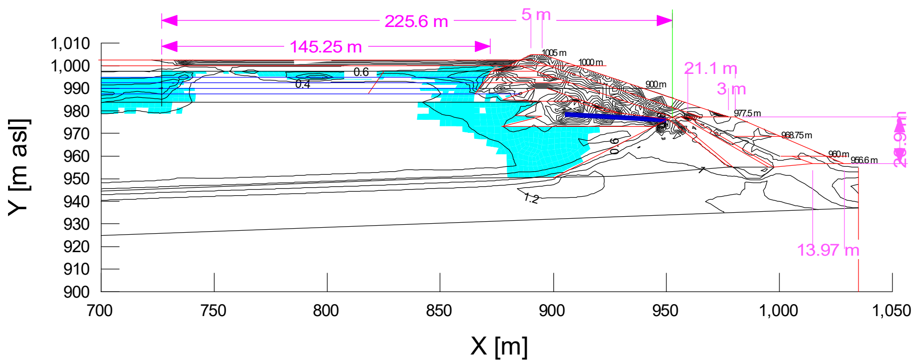

Figure 12: *Distribution of the q/p' ratio [-] with a liquefied zone (blue shaded region), for the state of stresses at the end of the earthquake action (dynamic liquefaction).*

For the state of dynamic liquefaction, the minimum stability is obtained (Geo-Slope SLOPE/W, v8, 2018) for the slope of the Toranica retention dam with a crest at 1.005 masl in the post-earthquake stage (Figure 13). The occurrence of liquefaction will cause a redistribution of the effective stresses, which will result in post-earthquake displacements in the geo-environment, horizontal and vertical, Figure 14, with crest settlement approximately 0.5 m.

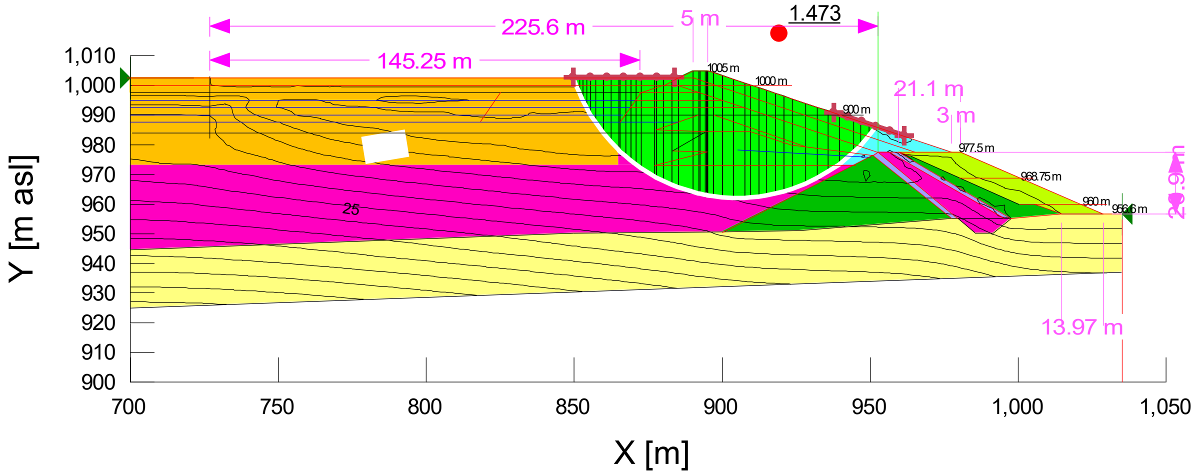

Figure 13: Critical slope slip surface, in the post-earthquake stage with a regular beach length of 150 m.

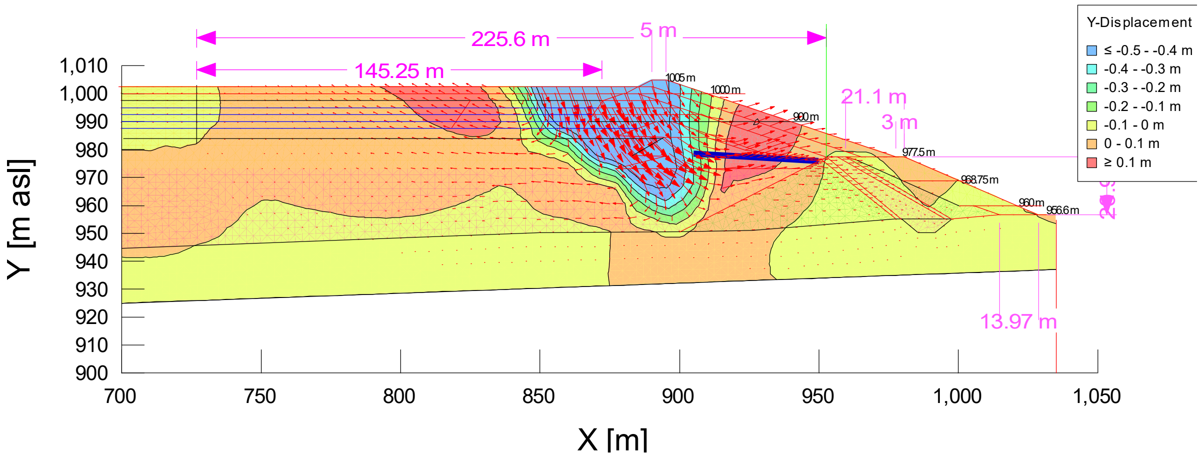

Figure 14: Distribution of additional vertical Y displacements and XY displacement vectors after earthquake action, with dissipation of liquefaction excess pore pressure.

5 CONCLUSIONS

With the initial state of stresses and measured pore pressures of the tailings dam for waste lagoon at elevation of 984 masl, the heightening was simulated in 7 loading 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 cycloned sand dam 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 growth, 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 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.

The general conclusion that with the heightening of the upstream (retention) dam of the Toranica 1 tailings dam, according to the adopted geometry and layout of the local materials, satisfactory static stability and seismic resistance is provided, according to the applicable design regulations, is based on the following facts.

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

The dynamic response of the geo-environment, determined by ELA, during SEE with peak ground acceleration PGA = 0.36 g and PGAy = 0.25 g, duration of t = 20 s, with synthetic accelerogram T=10,000_1, for standard state and regular scenario with beach length of approximately 150 m, with peak crest acceleration PCA = 0.65 g (at crest elevation 1.005 masl), i.e. dynamic amplification factor DAF = PCA/PGA = 1.8. The visual control that the dynamic response is correct is the diagram of the relative horizontal displacements, in range of +5 to –10 cm.

The permanent vertical displacement, caused by the inertial forces during the excitation, which is relevant for the assessment of the seismic resistance of the dam crest at 1,005.0 masl is the crest settlement, value of –0.65 m, is calculated by the Dynamic Deformation (DD) method. During the earthquake excitation, the average acceleration did not exceed the yield acceleration (where the stability factor is equal to 1.0), that is, the permanent deformations, calculated by the Newmark Method (NM) are equal to zero.

During an earthquake, there is an increase in pore pressure, which creates widened liquefaction zone after the earthquake. For the state of dynamic liquefaction, the minimum stability of the slope of the Toranica retention dam with a crest at 1.005 masl is obtained. For the critical sliding surface, it is value of 1,473, that is, it is greater than the one allowed for an incident extreme load Fper = 1.1.

The occurrence of liquefaction will cause a redistribution of effective stresses, which will result in post-earthquake displacements in the geo-environment, both horizontal and vertical, with vertical settlement in the crest at elevation 1.005 masl of 50 cm. The total permanent settlement in the crest is 65+50=115 cm. They are lower than the protective height from the normal water level to the dam crest of 2.5 m apropos there is no danger of a rapid and uncontrolled emptying of the tailings mud from the waste lagoon.

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