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APPLICATION OF "IN SITU" INVESTIGATIONS ON LIQUEFACTION MODELING AND ANALYSIS OF THE PRIMARY MEASURES TO INCREASE THE SEISMIC RESISTANCE OF THE TAILINGS DAMS

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SUMMARY

The tailings dams, due to the enormous volume of the waste lagoon, are earth-fill structures with highest potential hazard for the surrounding. However, the numerous reports of collapses of the tailings dams in the last three decades, all over the World, indicate that the structural (static and dynamic) safety and the liquefaction resistance was not controlled with the proper caution. In this research, the concept of collapse surface is used for liquefaction assessment, which is defined by two parameters, the angle of inclination of the collapse surface and steady-state strength. The steady-state strength of the different zones of the tailings dam is adopted from the results obtained from "In situ" investigations by Standard Penetration Test (SPT) and laboratory tests of fines. The primary measures that will drawdown the steady seepage phreatic line in the foundation zone of the critical for dynamic stability tailings dam, are analyzed. These primary measures, if they are feasible at the tailings facility, are the simplest and the most economical measures to reduce the liquefaction potential in the critical regions of the waste lagoon.

In this paper are presented results from the analysis of the dynamic response, the liquefaction assessment and the seismic resistance of the hydro tailings dam Topolnica, of the mine Buchim, Radovish. This tailings dam, in the east part of RN Macedonia, is formed by combination of downstream (in the first stage, dam 1) and upstream (in the second stage with two phases, dams 2-1 and 2-2) method of construction, with total height from the crest to the downstream toe of the dam of 141.2 m. For the analyzed hydro tailings facility, Topolnica, to increase the seismic resistance of the tailings dams, the first measure is to decrease waste lagoon water level, from 652 to 649 m ASL. The second measure is to increase the distance of the upstream seepage boundary condition, (with constant value of total hydraulic head of 649 m ASL), from 150 m to 700 m, upstream from the crown of the critical dam 2-2.

Key words: tailings dam, liquefaction, collapse surface concept

INTRODUCTION

Tailings dams are complex engineering structures, composed of initial dam, sand dam, waste lagoon, drainage system, outlet pipe for discharge of clear water, and structures for protection in case of inflow (external) water (*Petkovski, 2014a; Petkovski, 2014b*). The tailings, on one hand, due to the numerous structures of which they are composed, should be checked on large number of safety cases at static loading, similar as for conventional fill dams (*Petkovski, 2007*), and on other hand, due to the enormous volume of the waste lagoon, they are fill structures with the highest potential hazard for the surrounding (*Petkovski, 2015*). Due to the great importance of the tailings dams, one of the ICOLD's Technical Committees is exactly for tailings dams and deposit lakes - ICOLD Committee on Tailings dams and Waste Lagoons that has published several Bulletins, (*ICOLD, 1982; 1989; 1994; 1995; 1996; 2001*).

Due to the long construction period, the approach for conventional dams (for creation of water reservoirs) for confirmation of proper completion of the hydraulic structures – with full supervision of the construction and control of the first reservoir filling, as well and the assessment of the dam's proper behavior with construction parameters throughout comparison with monitoring data, at most cases is not applied fully in case of tailings dams. Unfortunately, this main difference between the conventional and tailings dams is amplified in case of technical solutions with combined construction method (*Petkovski, 2015*) and heightening (*Petkovski, 2012*) thus providing increase of the deposit space of the tailings dams. The investigation of the settlements in tailings dams body upon service period of the waste lagoon (*Petkovski, 2018*) is necessary to plan the dam crest heightening and to estimate limit values for the displacements. These estimated limit values have to be compared with the measured values within the monitoring process, so the proper conclusion can be drawn out for the regular behavior of the dam in the future period.

The purpose of this research is to investigate the waste lagoon water level and distance of the upstream seepage boundary condition influences on the liquefaction resistance of the hydro tailings dams. This relation is determined using the collapse surface concept for liquefaction assessment. This concept is defined by two parameters, the angle of inclination of the collapse surface and steady-state strength. The steady-state strength of the different zones of the tailings dam is adopted from the results obtained from “In situ” investigations by Standard Penetration Test and laboratory tests of fines content. In the text below, the analysis in the paper will be illustrated with data from the research of the dynamic response, the liquefaction assessment and the seismic resistance evaluation of the hydro tailings dam Topolnica, with combined construction method, of the mine Buchim, Radovish, RN Macedonia.

BASIC PARAMETERS OF THE TAILINGS DAM TOPOLNCA

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

The tailings dam is characterized with stage construction and combined construction method, by downstream progression in first stage and upstream progression at heightening from second stage, in two phases. The construction started with the initial dam, with foundation elevation 518.5 m ASL and crest elevation 558.5 m ASL. The construction of the sand dam in first stage, up to elevation 610 m ASL (I stage), was constructed in inclined layers, by progressing in downstream direction from the initial dam. Afterwards, the construction of the sand dam to elevation 630 m as (II stage, phase 1), due to the vicinity of village Topolnica to the downstream toe of the dam, was constructed by filling in upstream direction. At terminal stage is adopted sand dam crest at 654.0 m ASL (II stage, phase 2), by progression in upstream direction.
The overall dimensions of the representative cross section for structural (static and dynamic) analysis are length 801.4 m and height 141.2 m. The tailings dam Topolnica, with height of dam no. 2-2 above the foundation of initial dam of H_0 =654.0-518.5=135.5 m, is one of the highest tailings dams in Europe. The final height of the tailings dam no. 2-2, from crest to downstream toe, is H_2=654.0 - 512.8 =141.2 m, by what Topolnica tailings dam is highest dam in RN Macedonia. Namely, the highest conventional dam (for water reservoir), dam Kozjak, according to as built design from 2001, has height from dam crest to core foundation of 472.2 – 341.8 = 130.4 m. The enormous dimensions of the sand dam, heterogeneous composition of the geo-medium and combined construction method, downstream in stage I and upstream in stage II, obviously shows that dam Topolnica is one of the most complex and most important fill structures in RN Macedonia.

The basic and detailed design of the permanent spillway structure has not yet been prepared, but it has been concluded that it is possible that the maximum operating level (or normal elevation) in the waste lagoon could be in the interval from 649.0 to 652.0 m ASL. Namely, the crest of the dam no. 2-2 at 654.0 m ASL was planned in 2005, for the normal water level in the waste lagoon on 652.0 m ASL. The present water level (in August 2018) in the waste lagoon Topolnica is about 641-642 m ASL. At this level the surface of the lake is huge, about 1.0-1.3 M-m^2, and the volume of water, which could be replaced with the new tailings is about 12.0 M-m^3. The next mass of tailings is predicted on 40 M-t, which is about 25.8 M-m3. That is why for the mining purposes, the new normal level in the waste lagoon could be at 649.0 m ASL. At the same time, the access channel of the permanent spillway structure can be extended upstream from the crown of the dam 2-2, from the current 150 m to 700 m, and this will increase the distance of the upstream boundary seepage condition for additional 550 m. Therefore, at this moment, it is feasible and reliable to decrease the waste lagoon water level, from 652 to 649 m ASL and to move the upstream boundary seepage condition of the waste lagoon for 550 m, which means it is logical to analyze these two measures as possibilities to improve the liquefaction resistance of the tailings dam.

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

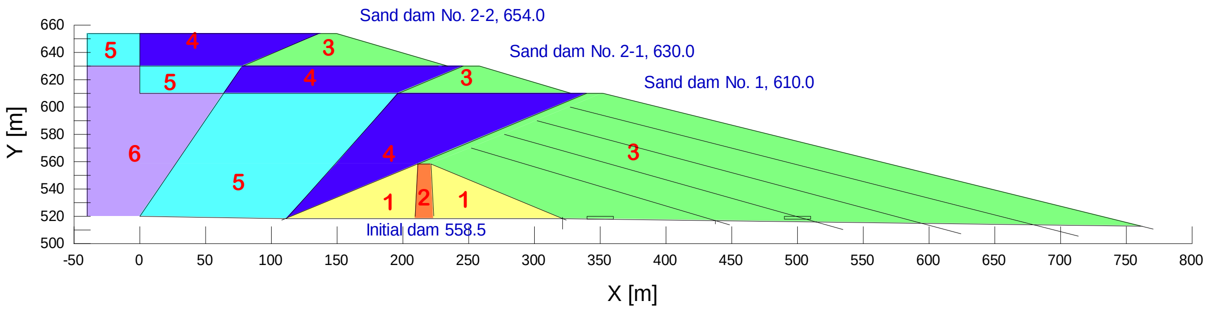

Fig. 1: Segments by six different materials. 1 – gravel in initial dam body, 2 – clay in initial dam core, 3 – sand in tailings dam, 4 – sand silt in beach, 5 – sand silt between the beach and lagoon and 6 – silt in waste lagoon

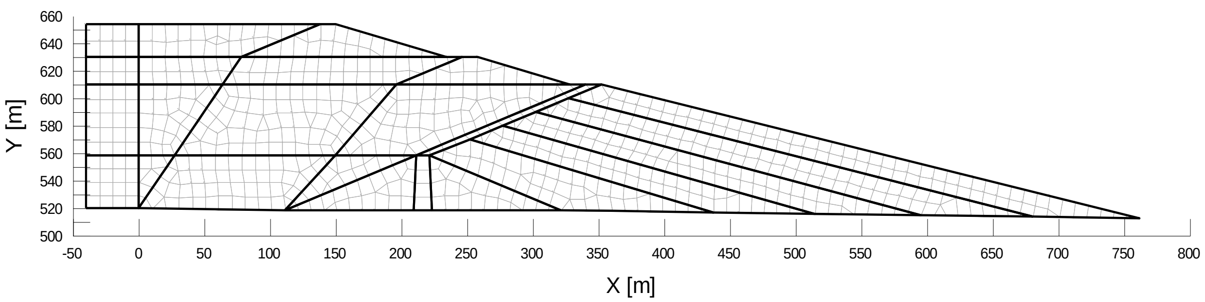

Figure 2: Discretization of the mediums for static analysis by FEM (Nodes=810, Elements=766), with upstream seepage boundary at 150 m from the dam 2-2

MODELING OF THE INITIAL STRESS STATE, PRIOR TO THE EARTHQUAKE

By the model, realistic progress of the tailings dam construction is simulated, i.e. the filling of the waste lagoon is by appropriate time delay upon sand dam construction. The upstream water saturation of the tailings due to the existing water inflow from river Topolnica in the tailings dam during progressing of the waste lagoon is adopted to be 2.0 m lower than the deposited tailings. Such upstream non-steady hydraulic boundary condition is necessary for the analysis of the effective stresses for the alternative with upstream water saturation of the tailings during construction, which is the service period of the structure. In the consolidation analysis, by analyzing the effective stresses in drained conditions in realistic time domain (*Geo Slope SIGMA/W, 2017*) is adopted water filling function in the waste lagoon, as variable upstream boundary condition for analysis of the non-steady seepage (*Geo Slope SEEP/W, 2017*). In such a complex and coupled analysis (by parallel mechanical and hydraulic response), in the same time are simulated: (a) stage construction, (b) development and dissipation of consolidation pore pressure, (c) change of the upstream hydrostatic pressure and (d) heterogeneous medium by irregular geometry. In the applied analysis, that simulates the tailings behavior most realistically, both the material parameters and the time component, i.e. the realistic construction dynamics, have significant influence.

The state with maximal potential hazard of the hydro system on the downstream river valley is the critical or the most important state for assessment of the seismic resistance of the tailings dam no. 2-2 for crest elevation 654.0 m ASL. It is a case when the waste lagoon is at maximal operating level (or normal water level at elevations 649.0 and 652.0 m ASL) and when steady seepage in the tailings dam is established. Then, the maximal values of the pore pressure are generated (Figs. 3-4) and for appropriate total stresses the geo-medium has minimal effective normal stresses (Figs. 5-6), i.e. it possesses minimal tangential resistance or reduced stiffness.

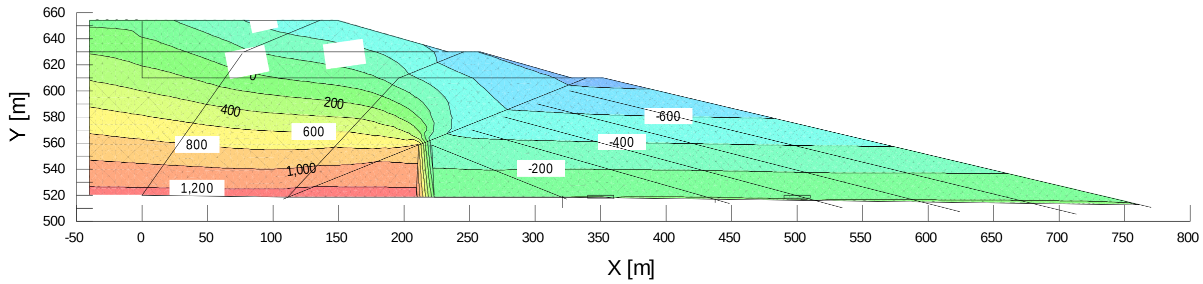

Fig. 3.1: Pore pressure distribution in kPa, for steady seepage in the tailings dam, at upper water elevation at 649.0 m ASL, with upstream seepage boundary at 150 m from the dam 2-2, Pw,max = 1,279.8 kPa

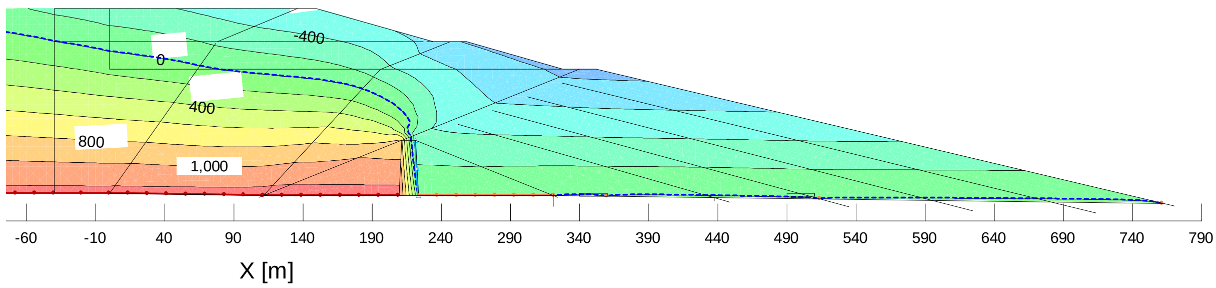

Fig. 3.2: Pore pressure distribution in kPa, for steady seepage in the tailings dam, at upper water elevation at 649.0 m ASL, with upstream seepage boundary at 700 m from the dam 2-2, Pw,max = 1,279.8 kPa

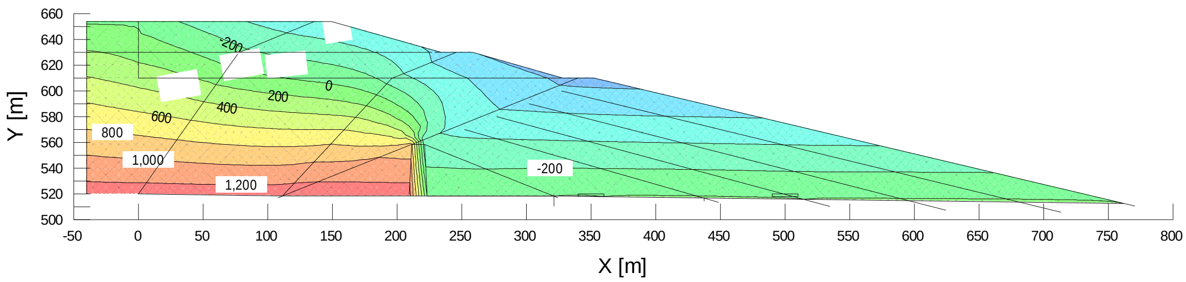

Fig. 4: Pore pressure distribution in kPa, for steady seepage in the tailings dam, at upper water elevation at 652.0 m ASL, Pw,max = 1,309.2 kPa

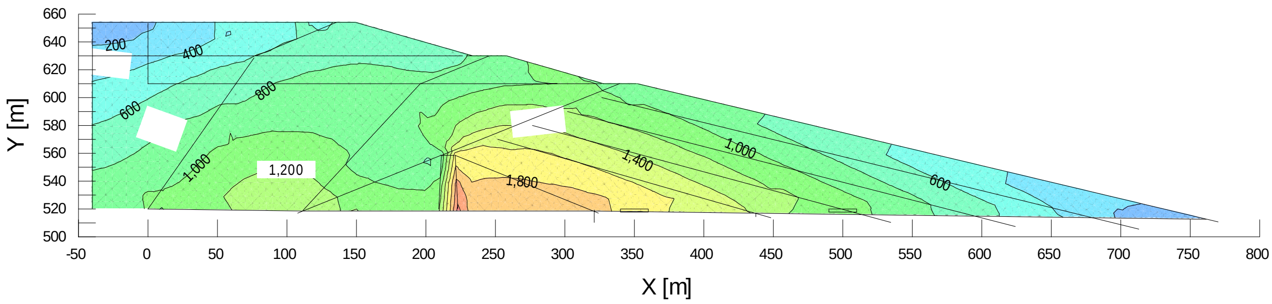

Fig. 5: Maximal effective stresses distribution, in kPa, for steady seepage in the tailings dam, at upper water elevation at 649.0 m ASL, S1`,max = 2,256.0 kPa

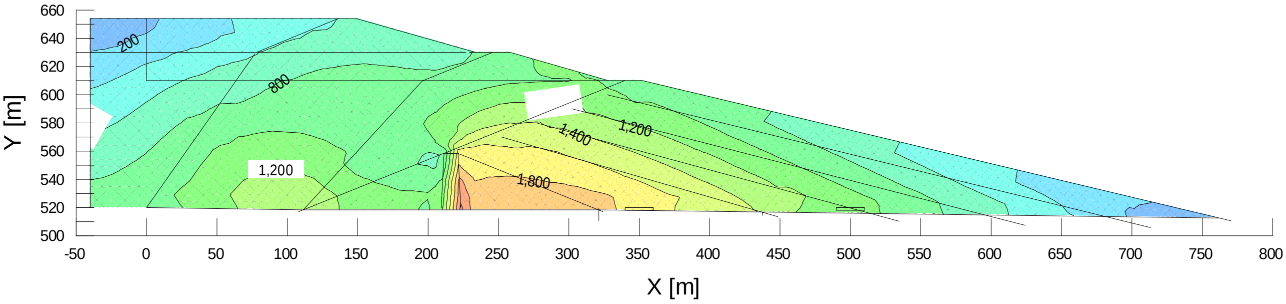

Fig. 6: Maximal effective stresses distribution, in kPa, for steady seepage in the tailings dam, at upper water elevation at 652.0 m ASL, S1`,max = 2,250.8 kPa

MODELING OF THE DAM RESPONSE AT ACTION OF A STRONG EARTHQUAKE – SEE

In the model for dynamic analysis of fill dams in time domain is applied program Quake (*Geo Slope QUAKE/W, 2017*). In the paper, having in mind the size and importance of dam Topolnica, as well as the available dynamic material parameters it is adopted the dynamic response of the dam to be determined by application of “Equivalent Linear Analysis” (ELA). The approach applied in the present analysis for determination of the permanent deformations during the seismic excitation, not only for the potential sliding body, but also for any node within the fill dam, is the method of “Dynamic Deformation Analysis” (DDA), which is successive non-linear redistribution of the stresses. By such method, for geo-medium discretized by finite elements, are calculated deformations caused by forces in nodes, calculated by the incremental stresses in the elements. Thus, by application of non-linear model, for each time step of the dynamic response of the structure is obtained new state of the total stresses and pore pressure. By the differences of the effective stresses in two successive time steps are obtained incremental forces, resulting in deformations, in accordance with the chosen constitutive law for dependence stress – strain. So, for each loading case during the dam’s dynamic response are produced elastic and eventual plastic strains. If dynamic inertial forces cause plastic strains, then in the geo-medium will occur permanent deformations. The permanent displacements, at any point in the dam and at end of the seismic excitation, are cumulative sum of the plastic deformations.

In this analysis, for the assessment of the “Liquefaction Potential”, which is strongly influenced by the initial stress state, the "Collapse Surface Concept" is applied. In this concept, the slope of the "Critical State Line" in the q (p ') stress space is equal to:

$$M = (6 * \sin\varphi') / (3 - \sin\varphi') \quad (1)$$

Where, the critical state line is:

$$q_{CSL} = M * p' \quad (2)$$

$$q = (\sigma_1 - \sigma_3) \quad (3)$$

is a strain deviator and represents the shear of the soil material,

$$p' = (\sigma'_1 + \sigma'_2 + \sigma'_3) / 3 \quad (4)$$

is a mean effective stress, which is defined in terms of effective principal stress, and φ' is conventional peak effective strength parameters (angle of internal friction). In the case of monotonic static loading in undrained conditions, increases in stresses occur up to the "collapse point", where the structure of the granules collapses. After the "collapse point", a sudden increase in pore pressure occurs and the strength rapidly falls to point of "Steady State Strength". Another way of describing this is that liquefaction is initiated at the "collapse point". According to *Sladen, D'Hollander and Krahn (1985)*, the straight line from "Steady State Strength" point through the "collapse point" of a soil material at the same initial void ratio, but consolidated under different confining pressures, is called "Collapse Surface", or according to *Vaid and Chern (1983)* is called "Flow Liquefaction Surface".

A cyclic loading can also lead to liquefaction. With increasing of the pore-pressure (under earthquake), cyclic stress path intersects the "Collapse Surface". Then the material will liquefy, and the strength will suddenly fall to "Steady State Strength" point. The input parameters in the "Collapse Surface Concept" are "steady state strength" (Css) in kPa and collapse surface angle (φ_L) in degrees, which determine the slope of the "Collapse Surface" or "Flow Liquefaction Surface" in the q-p' stress space, where the deviator stress for "Steady State Strength" is qss = 2*Css.

According to *Kramer, (1996)*, $\varphi_L \approx 2/3\ \varphi'$. While the values for (Css) were adopted according to the technical literature (*Fell et all, 2015*) on the (Css) dependence of $(N1)_{60} + \Delta(N1)_{60FinesContent}$, according to the research of *Idriss and Boulanger (2008)*, and *Seed (1987)*. Using the data on the number of impacts N determined by the "Standard Penetration Test" (SPT) and Fines content, from the renewed geotechnical investigations, the values of (Css) for the materials in the waste lagoon were calculated and adopted in the interval of 10-20 kPa, table 1.

Tab. 1: Input parameters of liquefaction potential of the waste lagoon materials, according to the CSC

Number		1	2	3	4	5	6
material		gravel	clay	sand	sandy silt	silty sand	silt
Segment or region		initial dam	initial dam	tailings dam	beach	beach, lagoon	waste lagoon
φ	o	34.0	18.0	38.0	30.0	25.0	20.0
$(N1)_{60}$						9.4	6.7
$\Delta(N1)_{60FinesContent}$						1.5	1.5
$(N1)_{60} + \Delta(N1)_{60FinesContent}$						10.9	8.2
Css	kPa				20.0	15.0	10.0
φ_L	o				18.0	15.0	12.0

With the values adopted (table 1), Critical State Line and Collapse Surface are determined for potentially liquefied materials in the waste lagoon, and the values for the dimensionless parameter (q/p'), when the materials become liquefied. Each zone with (q / p') above the "Collapse Surface" is liquefied and possesses the steady state strength. Each zone with (q / p') under "Collapse Surface", but above "Steady State Strength" is potentially liquefied and can pass over "Collapse Surface" with increasing of pore-pressure. Each zone with (q / p') under "Steady State Strength" is not potentially liquefiable, and when the pore pressure increases, the shear strength depends on φ' and c' - the peak effective strength parameters. From the parameter (q / p'), it can be concluded that in the zones of the mixture of materials in the waste lagoon, the values of the parameter (q / p') in the interval from 0.5 to 1.2 can be expected to liquefaction. That is, if the initial (or pre-earthquake) state yields values for (q / p') close to 0.50 (for a silt), 0.64 (for silty sand) and 0.78 (for sandy silt), then in the event of strong earthquakes and generating an excess pore pressure, in these zones will develop the liquefaction, Figure 7 and Figure 8, where the dotted lines are phreatic lines of steady seepage.

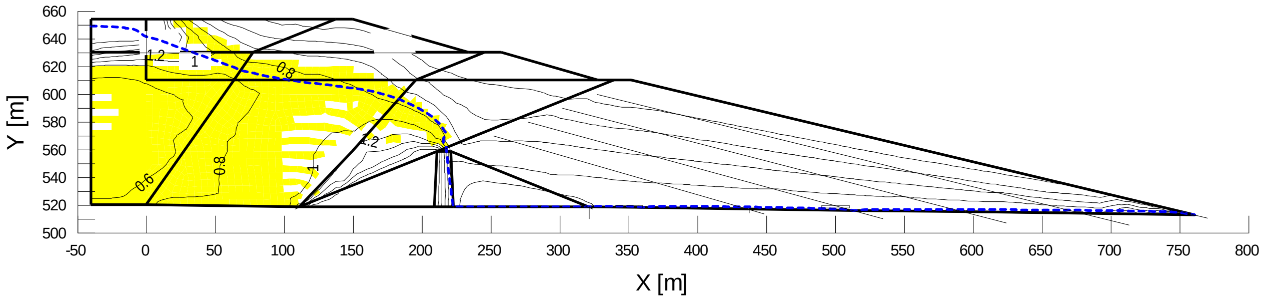

Fig. 7.1: Distribution of the parameter q / p '[-] with the liquefaction zone, for the initial stress state and steady seepage for water level in the lagoon on 649.0 m ASL, with upstream seepage boundary at 150 m from the dam 2-2

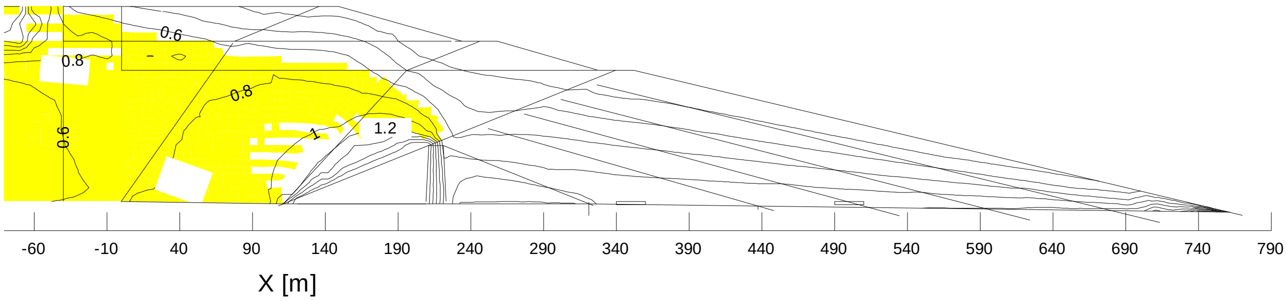

Fig. 7.2: Distribution of the parameter q / p '[-] with the liquefaction zone, for the initial stress state and steady seepage for water level in the lagoon on 649.0 m ASL, with upstream seepage boundary at 700 m from the dam 2-2

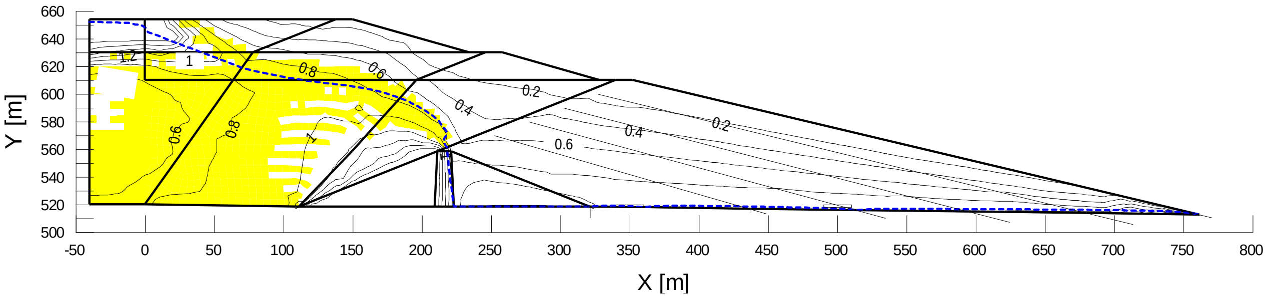

Fig. 8: Distribution of the parameter q / p '[-] with the liquefaction zone, for the initial stress state and steady seepage for water level in the lagoon on 652.0 m ASL

RESULTS FROM DYNAMIC BEHAVIOUR AND POST-EARTHQUAKE STABILITY ANALYSIS

Here below is presented the dam response at action of Maximum Credible Earthquake (MCE) or Safety Evaluation Earthquake (SEE) - or Synthetic earthquake Z2-EC81 (EuroCode8, type 1), with PGAx = 0.40 g, PGAy = 0.27 g, and duration of t = 25 s. The dynamic response is analyzed in the crest edge of dam no. 2-2 at elevation 654.0 m ASL, Figure 9 and Figure 10. The permanent displacement, obtained by Dynamic deformation analysis (Figs. 11-12), is a key parameter for assessment of the seismic resistance of the embankment dam, and is studied in the critical point from where an uncontrolled emptying of the lagoon is possible – upstream edge of the dam crest No. 2-2, at elevation 654.0 m ASL.

During the earthquake (MCE/SEE) there is an increase in the pore-pressure, creating a liquefaction zone, after the earthquake (Figure 13). The appearance of liquefaction will cause redistribution of the effective stresses, which will result in post-earthquake displacements in the dam (Figure 14). In order to assess the seismic resistance of the dam, the crown settlement is crucial due to the liquefaction phenomenon, estimated at about 20 cm.

The granules collapses of the liquefied materials in the waste lagoon cause change of the strength parameters along the critical slide surface. The increase of pore-pressure and the decrease of steady state strength, after the earthquake, results in decreasing of the stability of the slope (*Geo-Slope SLOPE/W, v8, 2018*) of the tailings sandy dam (Figs. 15-16).

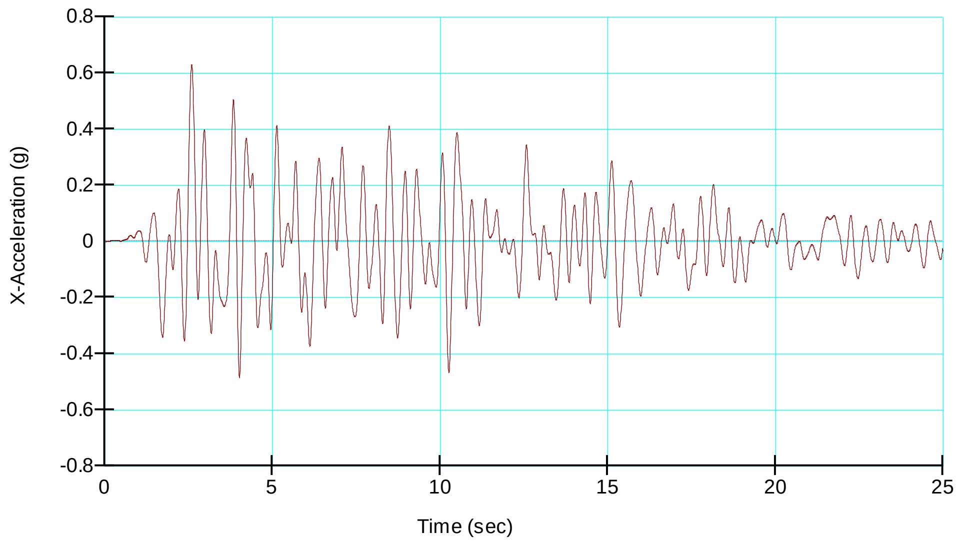

Fig. 9: Absolute acceleration a [g] ÷ t [s] in a horizontal direction, dam 2-2, elevation 654.0 m ASL, for the initial water level in the lagoon on 649.0 m ASL

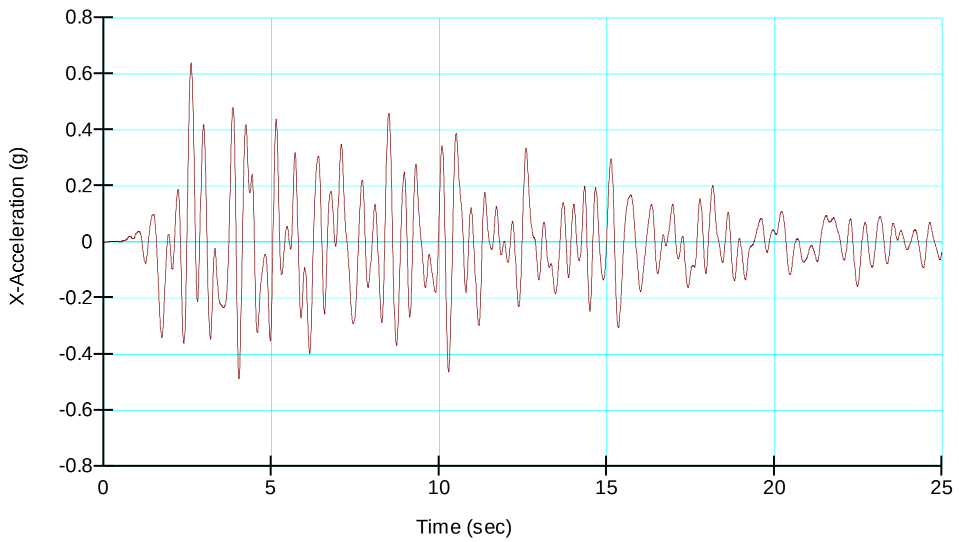

Fig. 10: Absolute acceleration a [g] ÷ t [s] in a horizontal direction, dam 2-2, elevation 654.0 m ASL, for the initial water level in the lagoon on 652.0 m ASL

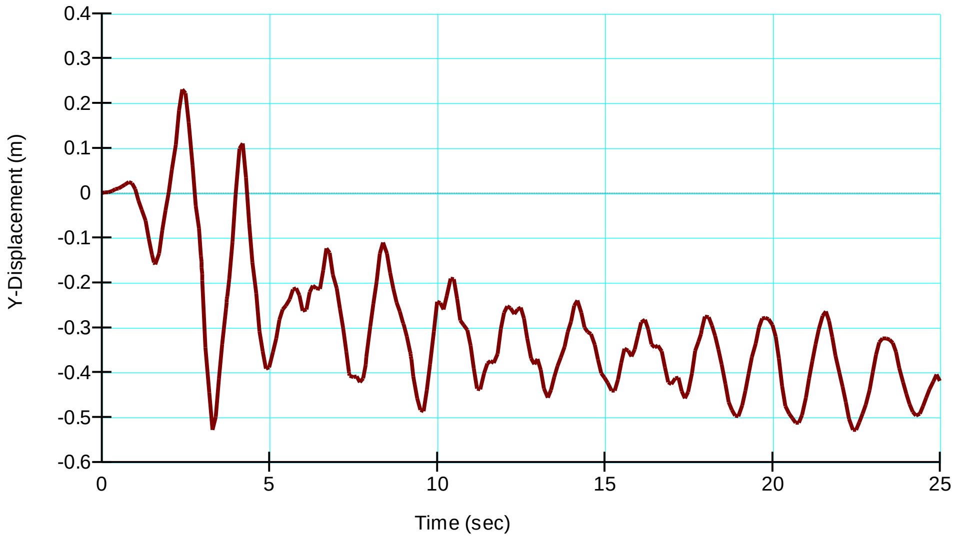

Fig. 11.1: Permanent vertical displacements obtained by the dynamic deformation method, Y [m] ÷ t [s], in the upstream crest edge of the dam 2-2, at level 654.0 m ASL, for the initial water level in the lagoon on 649.0 m ASL, with upstream seepage boundary at 150 m from the dam 2-2

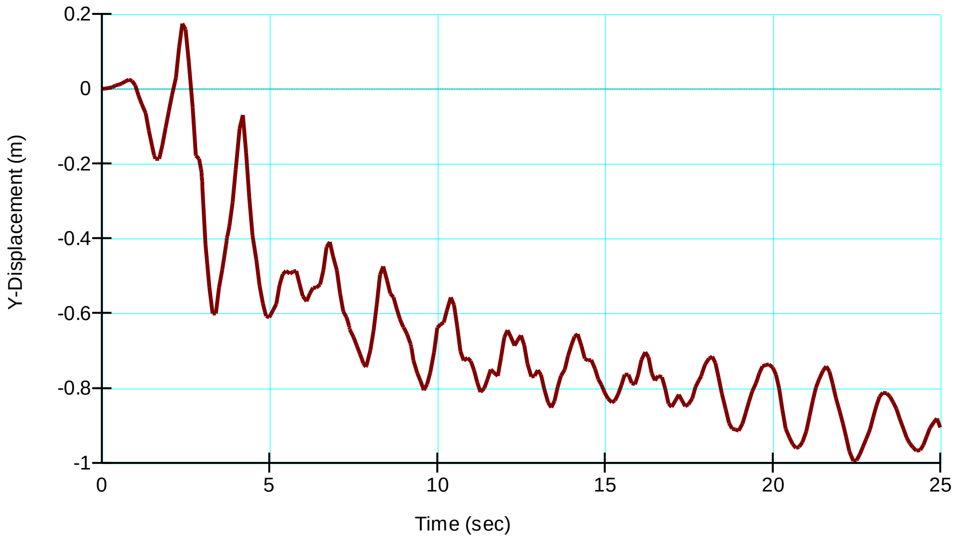

Fig. 11.2: Permanent vertical displacements obtained by the dynamic deformation method, Y [m] ÷ t [s], in the upstream crest edge of the dam 2-2, at level 654.0 m ASL, for the initial water level in the lagoon on 649.0 m ASL, with upstream seepage boundary at 700 m from the dam 2-2

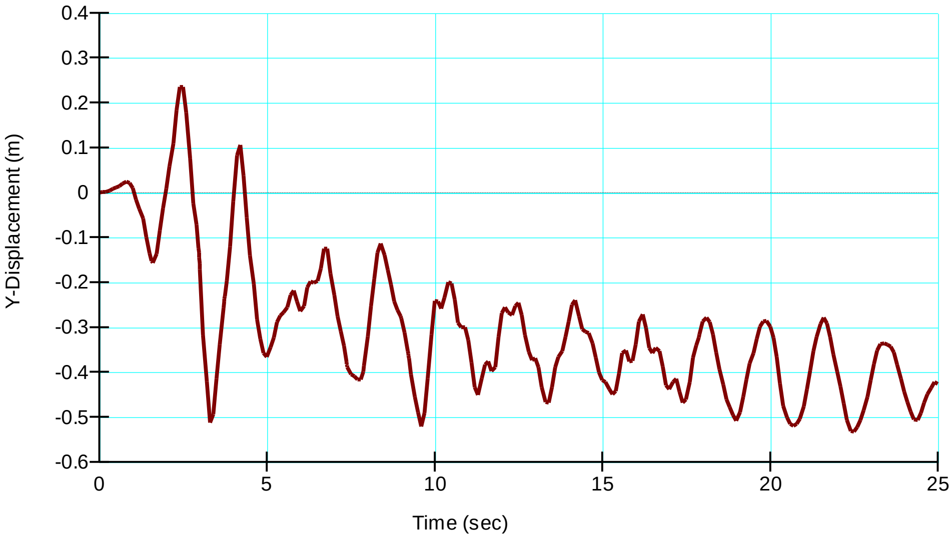

Fig. 12: Permanent vertical displacements obtained by the dynamic deformation method, Y [m] ÷ t [s], in the upstream crest edge of the dam 2-2, at level 654.0 m ASL, for the initial water level in the lagoon on 652.0 m ASL

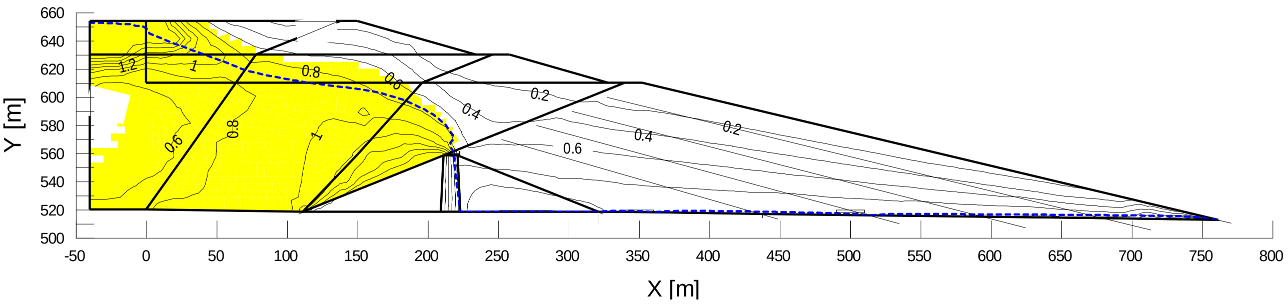

Fig. 13: Distribution of the parameter q / p' [-] with the liquefaction zone after the strong earthquake, for the initial steady seepage for water level in the lagoon on 652.0 m ASL

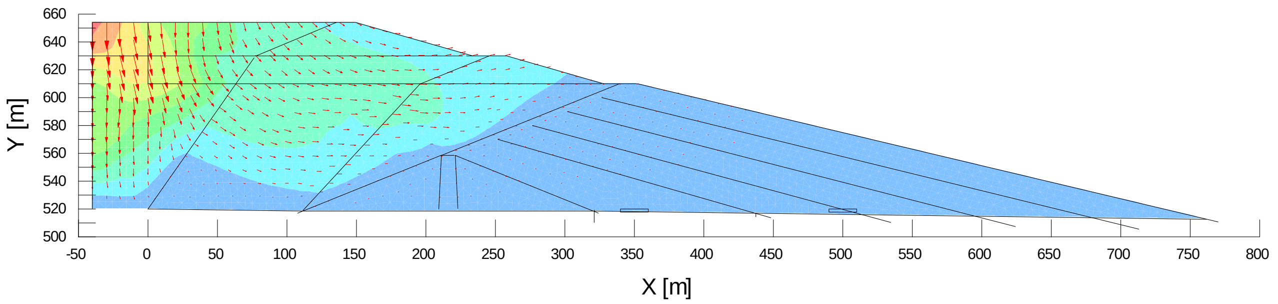

Fig. 14: The direction and intensity of the resulting displacements XY, after the earthquake, for the initial steady seepage for water level in the lagoon on 649.0 m ASL

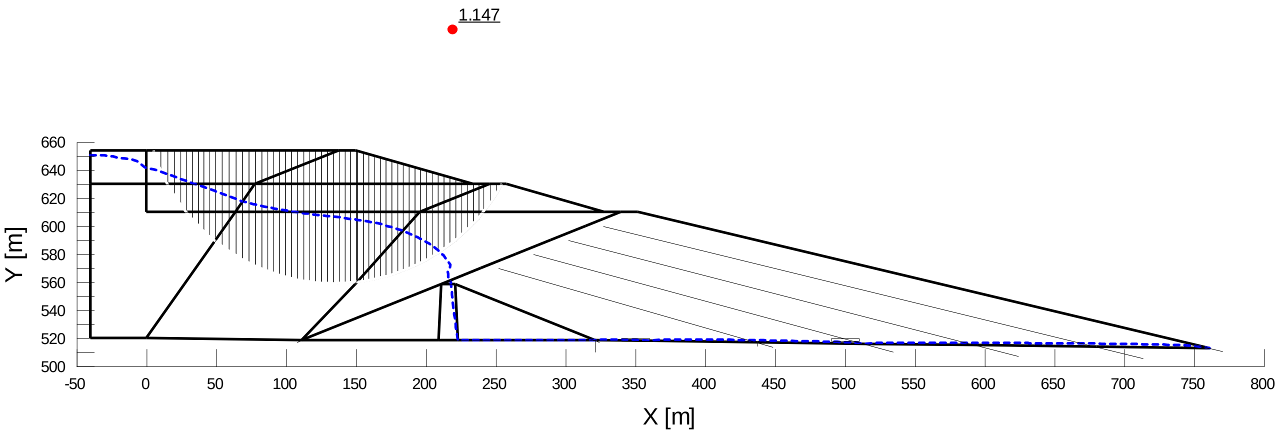

Fig. 15.1: Critical sliding surface, in the post-earthquake phase, with a stability factor F = 1.147, for the initial steady seepage for water level in the lagoon on 649.0 m ASL, with upstream seepage boundary at 150 m from the dam 2-2

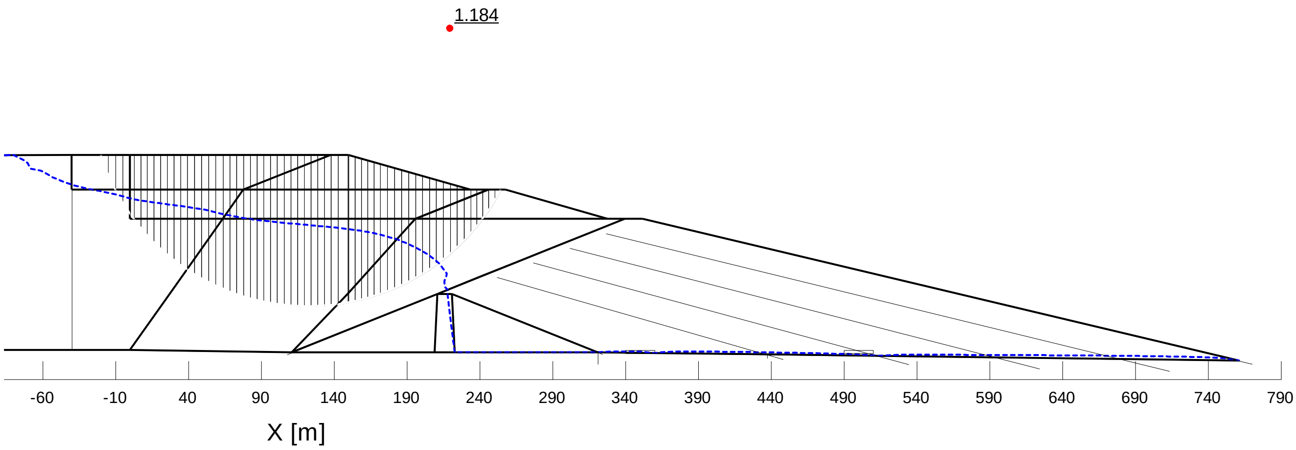

Fig. 15.2: Critical sliding surface, in the post-earthquake phase, with a stability factor F = 1.184, for the initial steady seepage for water level in the lagoon on 649.0 m ASL, with upstream seepage boundary at 700 m from the dam 2-2

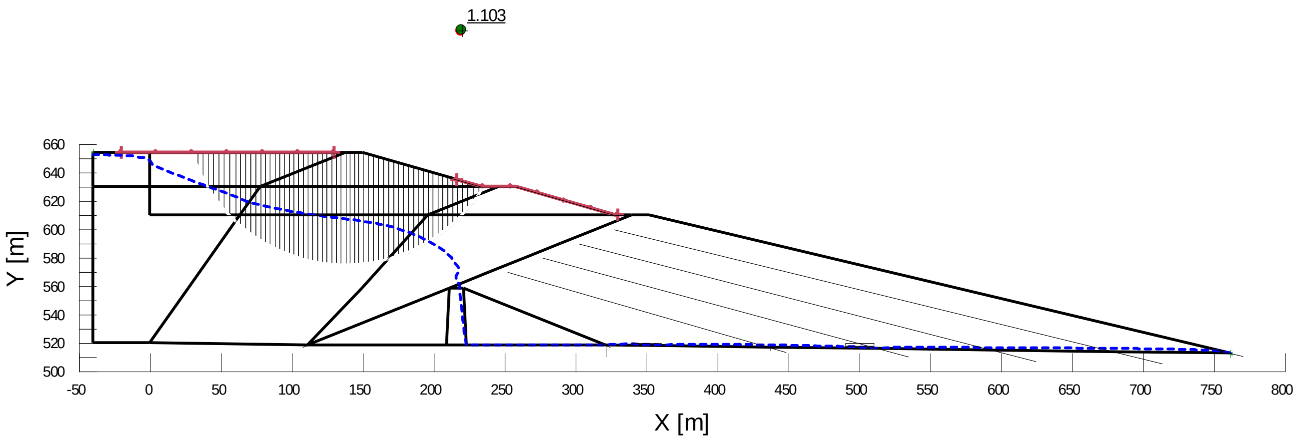

Fig. 16: Critical sliding surface, in the post-earthquake phase, with a stability factor F = 1.103, for the initial steady seepage for water level in the lagoon on 652.0 m ASL

CONCLUSIONS

The cumulative settlement in the crest at 654 m ASL, caused by catastrophic earthquake, are sum of: (1) additional compaction and reduced stiffness at materials on cyclic action Y1 = 70 cm, calculated by previous approximate approach, (2) dissipation of the pore excessive pressure caused by the liquefaction phenomena Y2 = 20 cm, determined by this research, and (3) permanent displacements caused by dynamic inertial forces during earthquake Y3=50 cm, also determined by the present analysis (for the normal water level at 652 m ASL). The cumulative settlements in the crest at 654 m ASL are Ys = Y1+Y2+Y3 = 70+20+50 = 140 cm. So, the height of 2 m (from the dam crest at 654 m ASL to the highest level of tailings silt in the lagoon 652 mnv) is not reached, i.e. there is no danger of rapid (uncontrolled) flow of silt from the waste lagoon during action of catastrophic earthquake, independent whether the initial stress state (prior the earthquake) and steady seepage for water level in the lagoon is 649 or 652 m ASL.

The safety factor of the downstream slope of the tailings sandy dam No. 2-2, in the post-earthquake state, with the steady-state strength in liquefied zones of the waste lagoon (according to the model with a seepage boundary condition about 150 m upstream from the crown of the dam 2-2), is $F_{L,0}$=1.103, for the initial water level in the lagoon at 652 m ASL.

With the first measure to improve liquefaction resistance, by lowering the maximum working water level in the lagoon, from 652 to 649 m ASL, the safety factor is $F_{L,1}$ = 1.147. We could notice only a slight improvement of stability with a small increase of the safety factor, from 1.103 to 1.147, i.e. a negligible improvement of 4%. The key conclusion about the influence of the variation of the initial water level in the lagoon for 3 m on the liquefaction resistance is negligible and that the calculated safety factor F_L for the liquefaction event due to strong earthquake is approximately equal to the permitted value for incidentally loading (F_{INC} = 1.1).

With the second measure to improve post-seismic stability, by increasing of the distance of the upstream seepage boundary condition, from 150 m to 700 m upstream from the crown of the dam no. 2-2, (with constant value of total hydraulic head of 649 m ASL), the stability factor is $F_{L,2}$ = 1.184. This measure will increase the safety factor of the tailings dam for 1.184/1.103, i.e. 7%, and the stability factor F_L for the liquefaction event is approximately equal to the permitted lower value for temporary loading ($F_{TEM,l}$ = 1.2). Our recommendations are as follow. First, the maximum working water level in waste lagoon to be 649 m ASL. Second, the minimal distance of water in the lagoon (or seepage boundary condition) to the crest of the dam No. 2-2 to be 700 m. And, last but not the least, the future period to be used to analyze the secondary measures to obtain the factor F_L for the liquefaction event, equal to the permitted higher value for temporary loading ($F_{TEM,2}$ = 1.3).

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ПРИМЕНА ТЕРЕНСКИХ ИСТРАЖИВАЊА ЗА МОДЕЛИРАЊЕ ЛИКВИФАКЦИЈЕ И АНАЛИЗА ПРИМАРНИХ МЕРА ЗА ПОВЕЋАЊЕ СЕИЗМИЧКЕ ОТПОРНОСТИ ЈАЛОВИШНИХ БРАНА

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Резиме

Јаловишне бране, због огромне запремине таложног језера, су насуте конструкције са највећим потенцијалним ризиком за околину. Међутим, бројни извештаји о рушењу јаловишних бране у последње три деценије, широм света, указују на то да конструктивна (статичка и динамичка) сигурност и ликвифакциона отпорност нису били контролирани са одговарајућим опрезом. У овом истраживању, за процену ликвифакције, користи се концепт површине лома, који је дефинисан са два параметра, углом нагиба површине лома и резидуалном чврстином. Резидуална јакост у различитим зонама јаловишне бране је усвојена на основу резултата добијених теренским испитивањима стандардним пенетрационим тестом (СПТ) и лабораторијским испитивањима садржаја ситних фракција. Анализиране су примарне мере које ће спустити стационарну филтрациону линију у зони темеља јаловишне бране, критичне за динамичку стабилност. Ове примарне мере, ако су изведиве у јаловишном постројењу, су најједноставније и најекономичније мере за смањење потенцијала ликвифакције у критичним регионима таложног језера.

У овом раду приказани су резултати анализе динамичког оговора, процене ликвифакције и сеизмичке отпорности хидројаловишне бране Тополница, рудника Бучим, Радовиш. Ова јаловишна брана, у источном делу РС Македоније, формирана је комбинацијом низводне (у првој етапи, брана 1) и узводне (у другој етапи са две фазе, бране 2-1 и 2-2) методе градње, укупном висином од круне до низводне тачке бране 141,2 m. За анализирано хидројаловишно постројење „Тополница“, за повећање сеизмичке отпорности јаловишних брана, прва мера је смањење нивоа воде у лагуни, са 652 на 649 m.н.м. Друга мера је да се повећа удаљеност узводног филтрационог граничног услова (уз константну вредност укупног хидрауличког притиска од 649 m НВ), са 150 m на 700 m, узводно од круне критичне бране 2-2.

Кључне речи: јаловишна брана, ликвифакција, концепт површине лома

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