Application of SPT results on liquefaction phenomenon modeling of tailings dams

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Abstract. *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 liquefiable resistance was not controlled with the proper carefulness. 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. 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 Republic of Macedonia, is formed by combination of downstream (in the first phase) and upstream (in the second phase) method of construction, with total height from the crest to the downstream toe of the dam of 141.2 m.*

1 INTRODUCTION

Tailings dams are complex engineering structures, composed of an 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, [1] and [2]. The tailings, on one hand, due to the numerous structures of which are composed, should be checked on great number of safety cases at static loading, similar as for conventional fill dams [3], and on other hand, due to the enormous volume of the waste lagoon, they are fill structures with highest potential hazard for the surrounding [4]. 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, [5], [6], [7], [8] and [9].

Due to the long construction period, the approach for conventional dams (for creation of water reservoirs) for confirmation of proper accomplishment 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, such main difference between the conventional and tailings dams is amplified

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in case of technical solutions with combined construction method [10] and heightening [11] 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 [12] 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 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 apply the collapse surface concept (CSC) 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 (SPT) and laboratory tests of fines. In the text below, 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, Republic of Macedonia.

2 BASIC PARAMETERS OF THE TAILINGS DAM TOPOLNCA

Tailings dam Topolnica of 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, mud and water without hydrocycling) is released in the upstream waste lagoon. In such way in the waste lagoon is done mechanical deposition of the finest particles and chemical purification of the used reagents, present in the tailings. In the past period in tailings dam Topolnica is deposited tailings volume over 130 millions m^3 and water is stored in volume of approximately 9 millions m^3.

The tailings dam is characterized with stage construction and combined construction method, by downstream progressing in first stage and upstream progressing at heightening from second stage, in two phases. The construction started with the initial dam, with foundation elevation 518.5 m and crest elevation 558.5 m. The construction of the sand dam in first stage, up to elevation 610 m (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 (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 H0 =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 H2 = 654.0 - 512.8 = 141.2 m, by what Topolnica tailings dam is highest dam in R. Macedonia. Namely, the highest conventional dam (for water reservoir), dam Kozjak, according to as built data 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 R. Macedonia.

Regarding the geotechnical parameters of the local materials, from which the tailings dam is constructed certain approximations are foreseen, thus contributing to simplification of the numerical experiment and in same time does not decrease 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 is prepared idealized cross section for structural analysis (static and dynamic), and the heterogeneous composition of the tailings dam is modeled with 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.

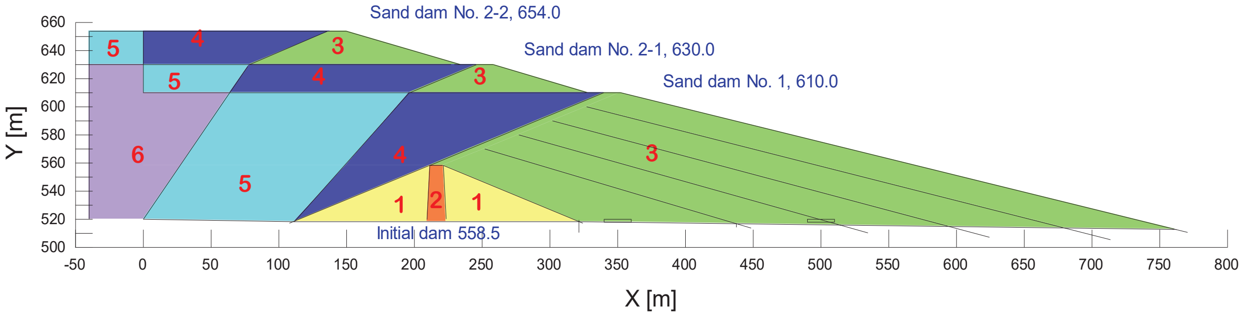

Figure 1: Segments by 6 different materials. 1 – gravel in initial dam body, 2 – clay in initial dam core, 3 – sand in tailings dam, 4 – sand silt in beach, 5 – sand silt between the beach and lagoon and 6 – silt in waste lagoon

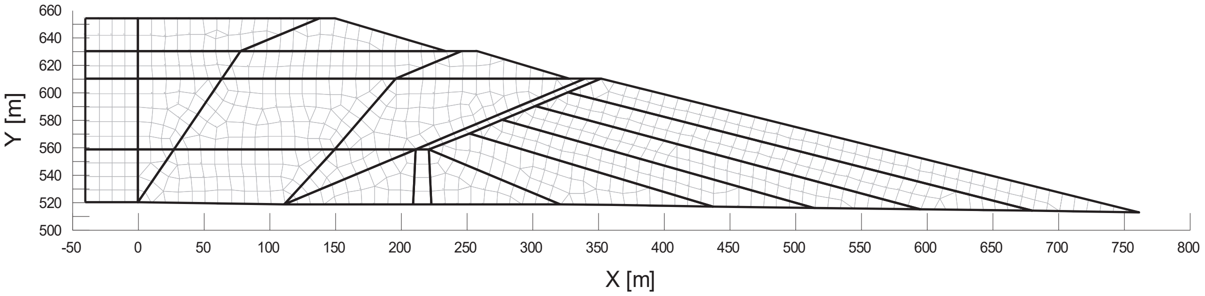

Figure 2: Discretization of the mediums for static analysis by FEM (Nodes=810, Elements=766)

3 MODELING OF THE INITIAL STRESS STATE, PRIOR TO THE EARTHQUAKE

By the model is simulated realistic progress of the tailings dam, i.e. 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 then 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 [13] is adopted water filling function in the waste lagoon, as variable upstream boundary condition for analysis of the non-steady seepage [14]. In such 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. It is a case when the waste lagoon is at maximal operating level (or normal water level at elevation 652.0 m) and when steady seepage in the tailings dam is established. Then, the maximal values of the pore pressure are generated (figure 3) and for appropriate total stresses (figure 4) the geo-medium has minimal effective normal stresses (figure 5), i.e. it possesses minimal tangential resistance or reduced stiffness.

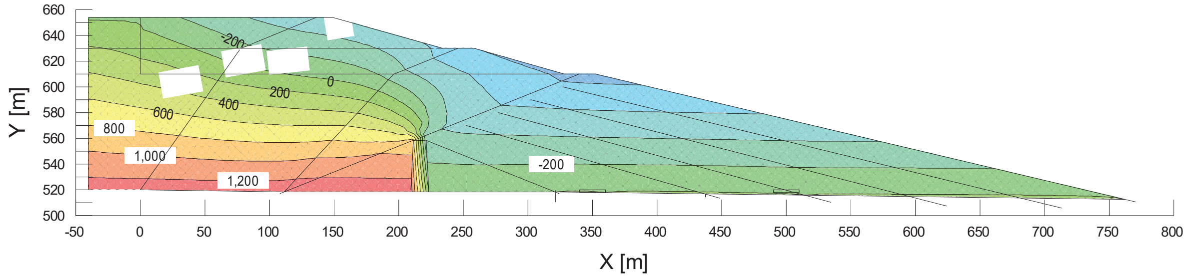

Figure 3: Pore pressure distribution in kPa, for steady seepage in the tailings dam, at upper water elevation at 652.0 m, Pw,max = 1,309.2 kPa

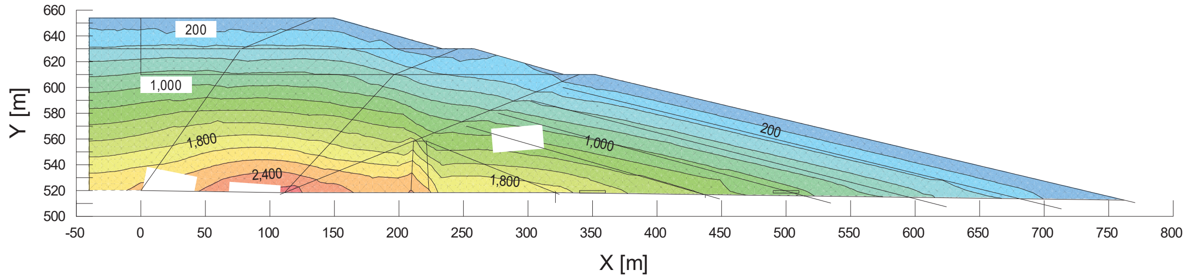

Figure 4: Maximal total stresses distribution, in kPa, for steady seepage in the tailings dam, at upper water elevation at 652.0 m, S1,max = 2,658.7 kPa

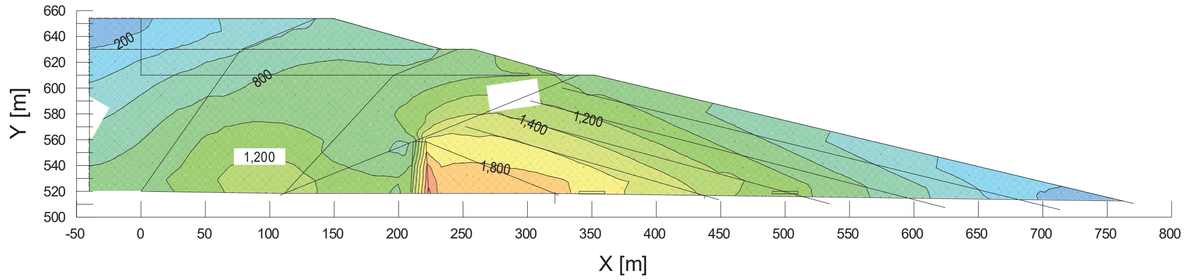

Figure 5: Maximal effective stresses distribution, in kPa, for steady seepage in the tailings dam, at upper water elevation at 652.0 m, S1`,max = 2,250.8 kPa

4 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 [15]. In the paper, having in mind the size and importance of dam Topolnica, as well and 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 stress – strain dependence. So, for each loading case during the dam dynamic response elastic and eventual plastic strains are produced. 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" (CSC) is applied. In this concept, the slope of the "Critical State Line" (CSL) in the q (p ') stress space is equal to:

$$M = (6 * \sin\varphi') / (3 - \sin\varphi') \tag{1}$$

Where:

$$q = (\sigma_1 - \sigma_3) \tag{2}$$

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

$$p' = (\sigma'_1 + \sigma'_2 + \sigma'_3) / 3 \tag{3}$$

is a mean effective stress, which is defined in terms of effective principal stress, and φ' is conventional peak effective strength parameter (angle of internal friction).

In the case of monotonic static loading in undrained conditions, increases in stresses occur up to the "collapse point" (CP), where the structure of the granules collapses. After the CP, a sudden increase in pore pressure occurs and the strength rapidly falls to point of "Steady State Strength" (SSS). Another way of describing this is that liquefaction is initiated at the CP. According to Sladen, D'Hollander and Krahn [16], the straight line from SSS point through the CP of a soil material at the same initial void ratio, but consolidated under different confining pressures, is called "Collapse Surface" (CS), or according to Vaid and Chern [17] and Kramer [18] is called "Flow Liquefaction Surface" (FLS).

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

According to Kramer, [18], $\varphi_L \approx 2/3\ \varphi'$. While the values for (Css) were adopted from the technical literature according to Fell [19] on the (Css) dependence of $(N1)_{60}$ + $\Delta(N1)_{60FinesContent}$, using the method of Idriss and Boulanger [20], where corrections for fines content is based on Seed [21]. 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.

Table 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
DN1(FC)						1.5	1.5
N1+DN1						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 (CSL) and Collapse Surface (CS) are determined for potentially liquefied materials in the waste lagoon, and the values for the dimensionless parameter (q / p'), when the materials become liquefied, figure 6. Each zone with (q / p') above the CS is liquefied and possesses the steady state strength (SSS). Each zone with (q / p') under CS, but above SSS is potentially liquefied and can pass over CS with increasing of pore-pressure. Each zone with (q / p') under SSS is not potentially liquefiable, and when the pore pressure increases, the shear strength depends on φ' and c' - the peak effective strength parameters.

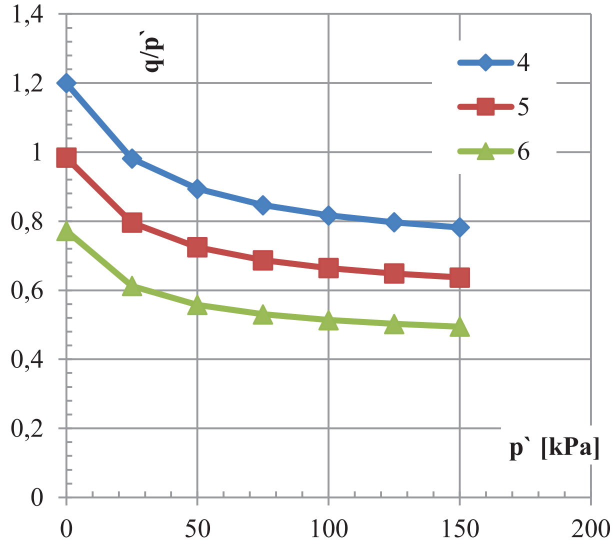

Figure 6: Values for the dimensionless parameter (q / p ') when the materials liquefied, Legend: 4 – sandy silt in beach, 5 – silty sand between the beach and lagoon and 6 – silt in waste lagoon

From figure 6, it can be concluded that the zones of the mixture of materials in the waste lagoon, with the values of the parameter (q / p ') in the interval from 0.5 to 1.2, are potentially liquefiable zones. 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.

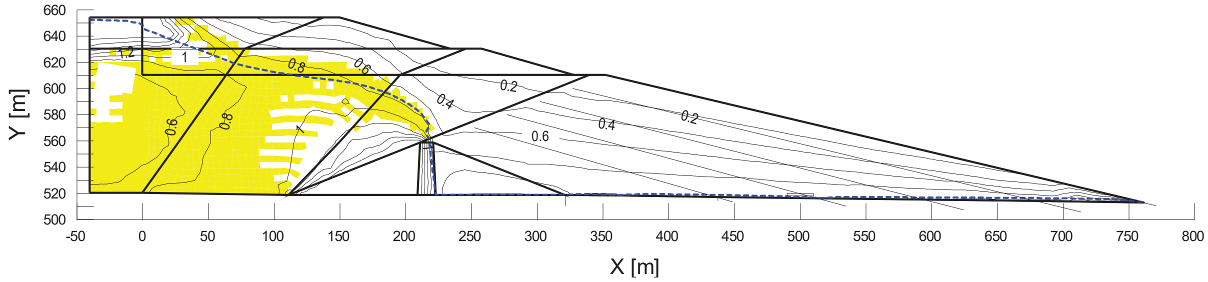

Figure 7: Distribution of the parameter q / p '[-] with the liquefaction zone, for the initial stress state and steady seepage for water level in the lagoon on 652.0 m

5 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, figures 8 and 9. The permanent displacement, obtained by Dynamic deformation analysis (figure 10), is key parameter for assessment of the seismic resistance of the embankment dam, and is studied in the critical point from where is possible uncontrolled emptying of the lagoon – upstream edge of the dam crest No. 2-2 at elevation 654.0 m.

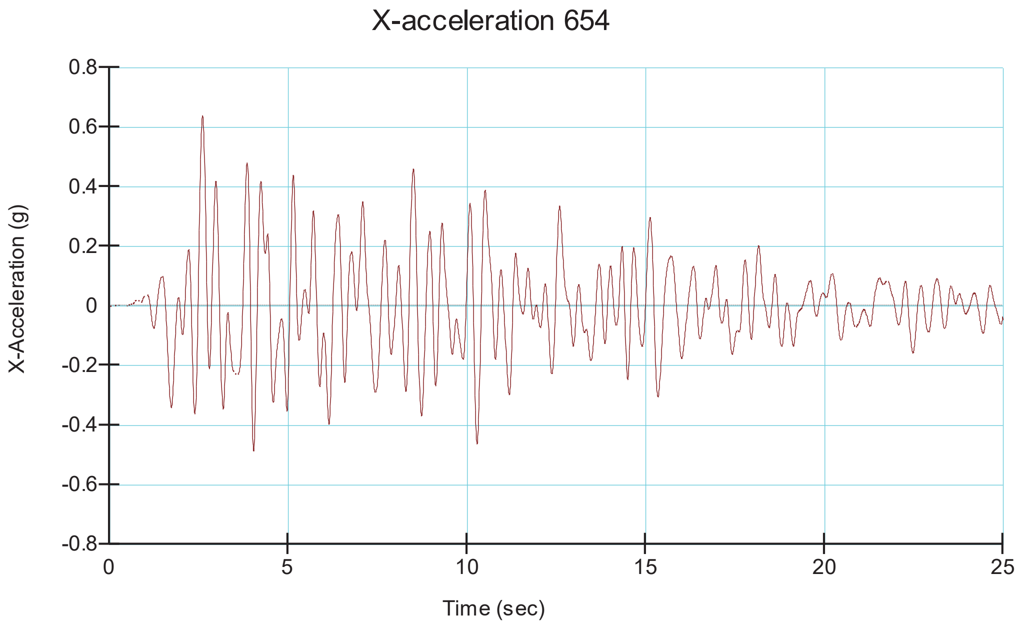

Figure 8: Absolute acceleration a [g] ÷ t [s] in a horizontal direction, dam 2-2, elevation 654.0 m

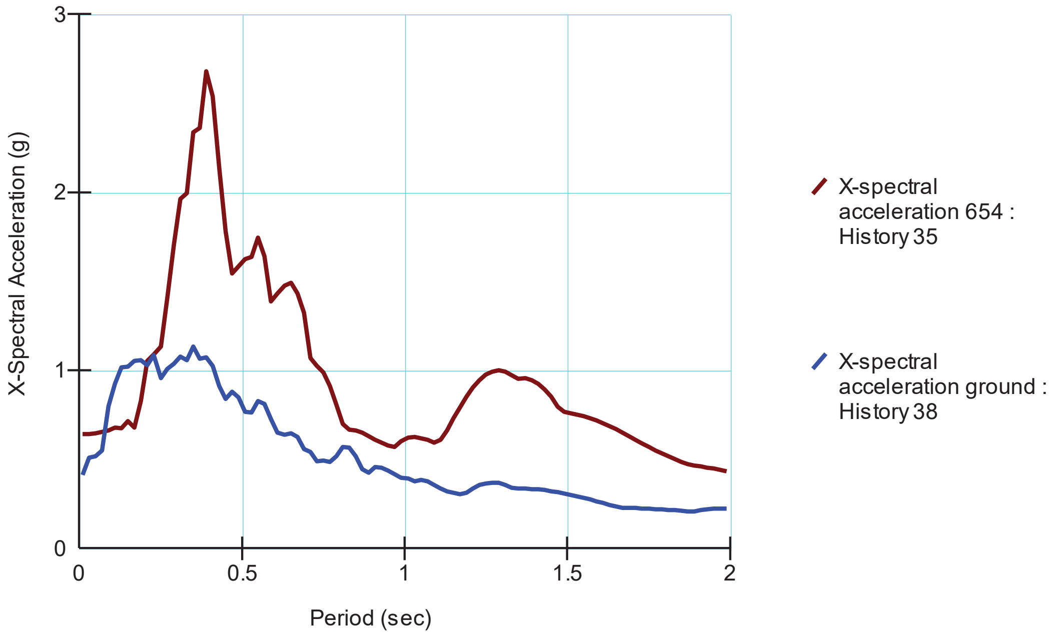

Figure 9: Spectrum of the acceleration response Sa [g] ÷ T [s] for DR = 0.05, in the rock base (excitation) and in the crown of dam 2-2 (response)

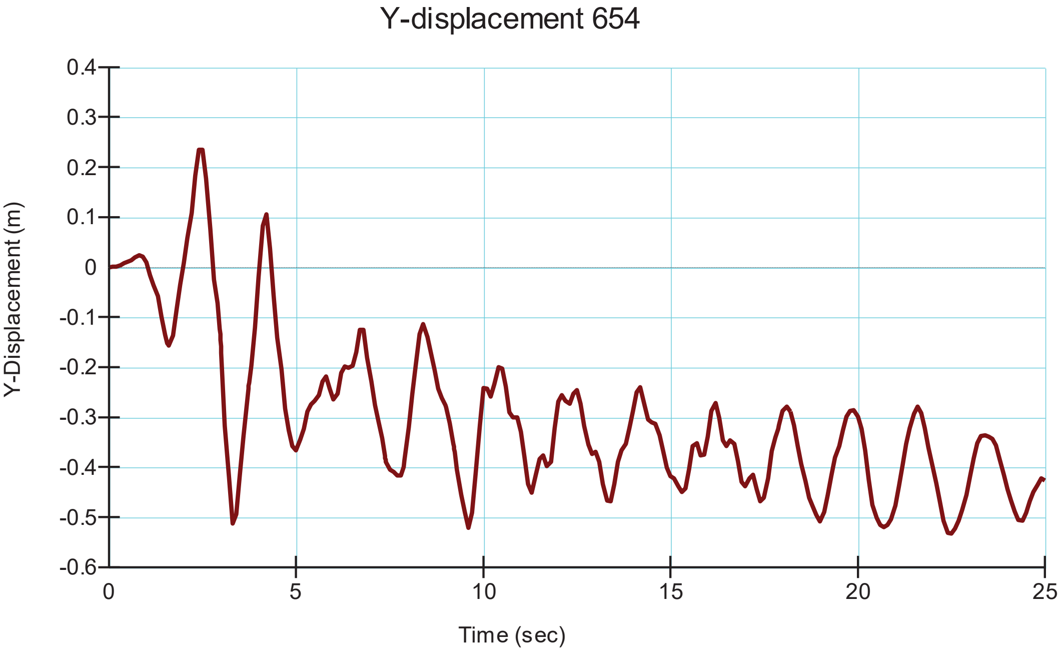

Figure 10: Permanent vertical displacements obtained by the dynamic deformation method, Y [m] ÷ t [s], in the upstream crest edge of the dam 2-2, at level 654.0 m

During the earthquake (MCE / SEE) there is an increase in the pore-pressure, creating a liquefaction zone, after the earthquake (figure 11). The appearance of liquefaction will cause redistribution of the effective stresses, which will result in post-earthquake displacements in the dam (figure 12). 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.

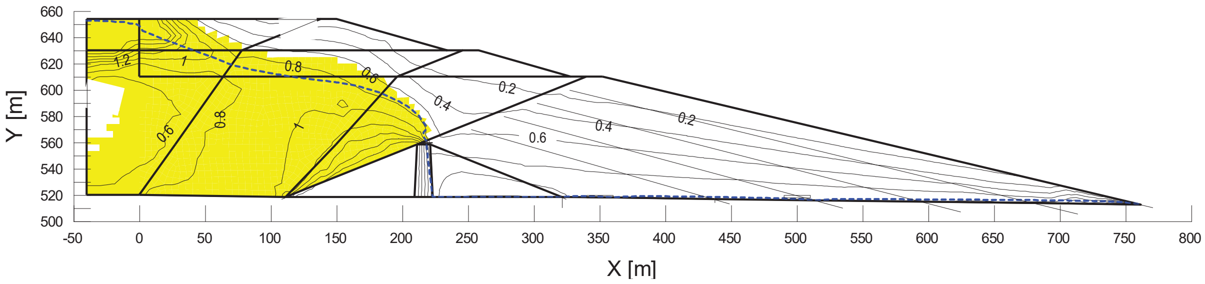

Figure 11: Distribution of the parameter q / p' [-] with the liquefaction zone after the strong earthquake

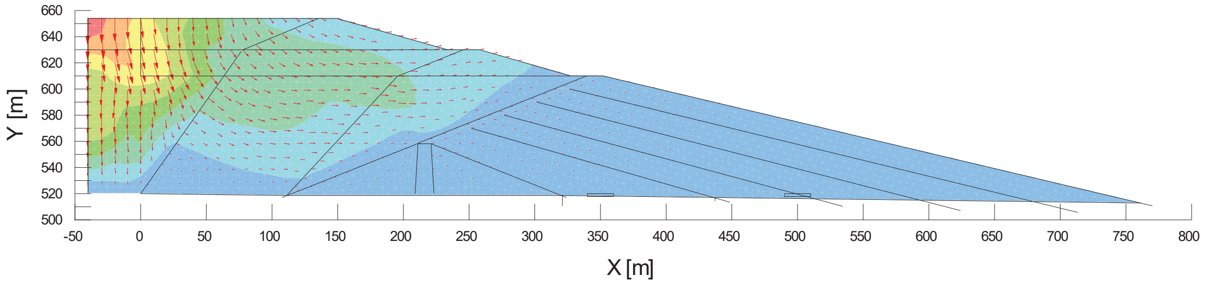

Figure 12: The direction and intensity of the resulting displacements XY, after the earthquake

The granules collapses of the liquefied materials in the waste lagoon cause change of the strength parameters (figure 13) along the critical slide surface. The increase of pore-pressure and the decrease steady state strength, after the earthquake, result to decrease of the stability of the slope [22] of the tailings sandy dam (figure 14).

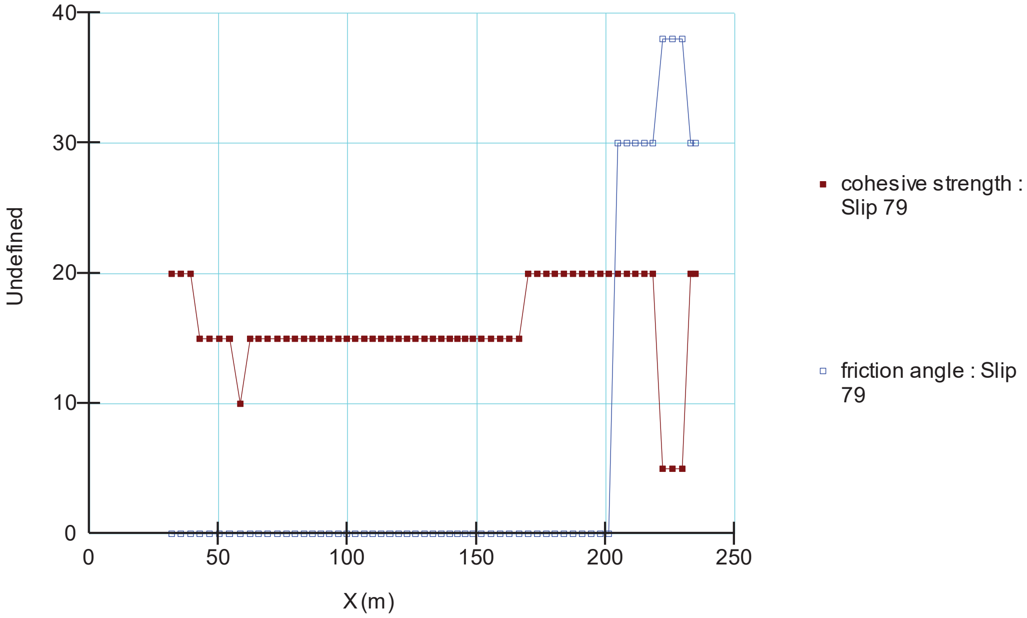

Figure 13: Distribution of strength parameters along the critical surface, cohesion in kPa and internal friction angle in degrees, after the strong earthquake

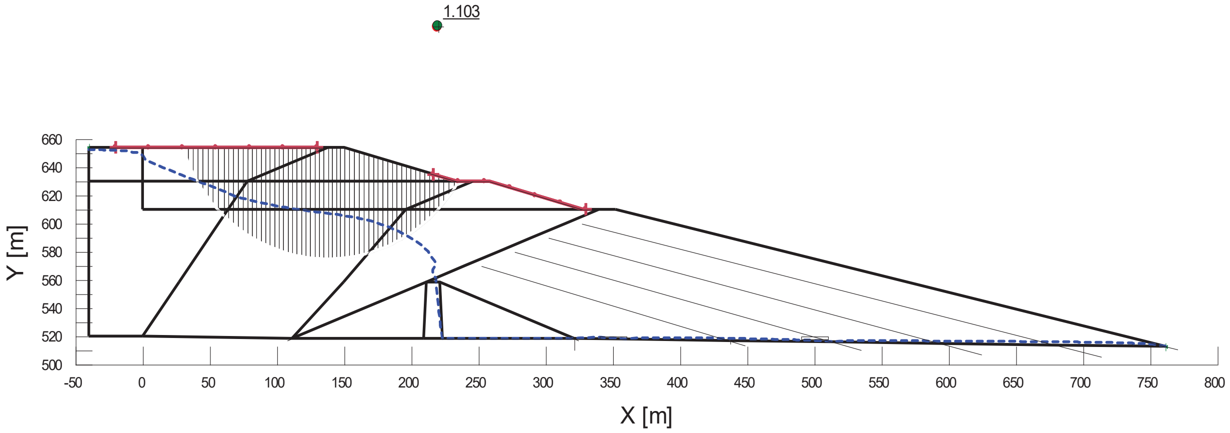

Figure 14: Critical sliding surface, in the post-earthquake phase, with a stability factor F = 1.103

6 CONCLUSIONS

The cumulative settlement in the crest at 654.0 m, caused by catastrophic earthquake, are sum of: (1) additional compaction and reduced stiffness at materials on cyclic action Y1 = 70.0 cm, calculated by previous approximate approach, (2) dissipation of the pore excessive pressure caused by the liquefaction phenomena Y2 = 20.0 cm, determined by this research, and (3) permanent displacements caused by dynamic inertial forces during earthquake Y3=50.0 cm, also determined by the present analysis. The cumulative settlements in the crest at 654.0 m are Ys =Y1+Y2+Y3=70.0+20.0+50.0 = 140.0 cm. So, the height of 2.0 m (from dam crest at 654.0 m to the highest level of tailings silt in the lagoon 652.0 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.

Stability 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 applied model with a water level on 652.0 m and about 150 m upstream from the crown of the dam), is 1.103. The calculated stability factor (FL) for the liquefaction event due to strong earthquake is approximately equal to the permitted value for incidentally and temporary loading (FL,per = 1.1). Therefore, the first measures to improve resistance against liquefaction, we recommend to be reduction of the normal water level elevation in the waste lagoon, from 652.0 to 649.0 m and distancing the upstream border filtration condition from 150 m to 700 m upstream from the crown of the dam no. 2-2. Our opinion is that these measures are the simplest and the most economical, and that will drawdown the steady seepage phreatic line in the foundation zone of the tailings sand dam No. 2-2 and could reduce the potential of liquefaction in the critical regions of the waste lagoon.

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