COMMISSION INTERNATIONALE
DES GRANDES BARRAGES

VINGT SIXIÈME CONGRÈS
DES GRANDS BARRAGES
Vienne, Juillet 2018

ASSESEMENT OF SEISMIC RESISTANCE OF COMBINED TAILINGS DAMS*

Ljupcho PETKOVSKI
Full professor, Chair of Hydraulic Structures
Ss Cyril and Methodius University, Civil Engineering Faculty – Skopje

Stevcho MITOVSKI
Assistant Professor, Chair of Hydraulic Structures
Ss Cyril and Methodius University, Civil Engineering Faculty – Skopje

REPUBLIC OF MACEDONIA

SUMMARY

The similarities between the tailings dams and the embankment dams for water storage have contributed a great number of procedures and techniques in the design, construction and maintenance of the conventional dams, to be applied to tailings dams. 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), filtration, hydrological and hydraulic safety were not controlled with the same rigor and carefulness – as for the embankment dams. This fact, in part, results from the long-term construction of the tailings dams, where as a building material is used sand obtained by separating of the waste material from floatation process during the exploitation of the mine. In this paper are presented results from the dynamic analysis and assessment of seismic resistance of the hydro tailings Topolnica, on the river Topolnica, in the east part of Republic of Macedonia. It is a tailings dam with a 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.

* *Évaluation de la résistance sismique des bassins de résidus combinés*

RÉSUMÉ

Les similitudes entre les bassins de résidus et les barrages de remblai pour le stockage de l'eau ont contribué à un grand nombre de procédures et de techniques dans la conception, la construction et l'entretien des barrages conventionnels, à appliquer aux bassins de résidus. Cependant, les nombreux rapports d'effondrements des barrages de résidus au cours des trois dernières décennies, partout dans le monde, indiquent que la sécurité structurelle (statique et dynamique), la filtration, l'hydrologie et l'hydraulique n'étaient pas contrôlées avec autant de rigueur et de prudence pour les barrages de remblai. Ce fait, en partie, résulte de la construction à long terme des digues à stériles, où l'on utilise comme matériau de construction du sable obtenu en séparant les déchets du processus de flottation pendant l'exploitation de la mine. Dans cet article sont présentés les résultats de l'analyse dynamique et l'évaluation de la résistance sismique des résidus hydroélectriques Topolnica, sur la rivière Topolnica, dans la partie orientale de la République de Macédoine. C'est un barrage de résidus avec une combinaison de méthode de construction en aval (dans la première phase) et en amont (dans la deuxième phase), avec une hauteur totale de la crête à la pointe aval du barrage de 141,2 m.

1. INTRODUCTION – TAILINGS DAM AS COMPLEX STRUCTURES

The tailings dams are complex engineering structures, composed of initial dam, sand dam, waste lagoon, drainage system, water conveyors for taking out of the cleared water and structures for protection in case of inflow (external) water. The tailings dams, on one hand, due to the numerous structures of which are composed, should be checked on great number of safety cases at static and dynamic loadings, similar as for conventional fill dams [1], and on other hand, due to the enormous volume of the waste lagoon, they are fill structures with highest potential hazard for the surrounding [2]. Due to the great importance of the tailings dams, one of the ICOLD's Technical Committees specifically deals for such hydraulic structures – ICOLD Committee on Tailings dams and Waste Lagoons, that has published 10 Bulletins, from [3] to [4].

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 behaviour with construction parameters through out comparation 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 in case of technical solutions with combined construction method [5, 6] and in case of heightening [7, 8] thus providing increase of the deposit space of the tailings dams.

The aim of the research is to determine the permanent displacement in the tailings dam body at action of strong earthquakes [9], in the post-service period, when the system dam and waste lagoon has the highest potential hazard for the surrounding and to assess the seismic resistance of the geo-medium. In the here below text, the paper will be illustrated with data from the research of the dynamic response of the tailings dam Topolnica of mine Buchim, Republic of Macedonia, with combined construction method (fig. 1).

Fig. 1.
Location map and map of Republic of Macedonia
Carte et plan de la République de Macédoine

2. TAILINGS DAM TOPOLNICA – BASIC PARAMETERS

Tailings dam Topolnica of mine Buchim, Radovish, commissioned in 1979, is created by deposition of the flotation pump. By the method of pulp hydro-cycloning 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 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 (fig. 2) is deposited tailings volume over 130 millions m^3 and water is stored in volume of approximately 9 millions m^3.

Fig. 2
Crest and waste lagoon of tailings dam Buchim, March, 2016
Crête et lagune de déchets du barrage de résidus Buchim, mars 2016

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 of the sand dam in initial stage, up to elevation 610 masl (I stage), fig. 4, was constructed in inclined layers, by progressing in downstream direction from the initial dam, fig. 3, with foundation elevation 518.50 masl and crest elevation 558.5 masl. Afterwards, the construction of the sand dam till elevation 630 masl (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, fig. 5. At terminal stage is adopted sand dam crest at 654.0 masl (II stage, phase 2), by progression in upstream direction, fig. 6.

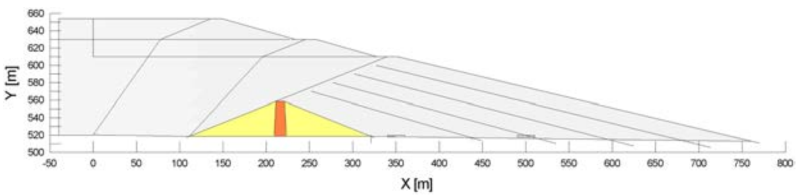

Fig. 3
Construction of initial dam till elevation 558.5 masl
Construction du barrage initial jusqu'à l'altitude 558.5 masl

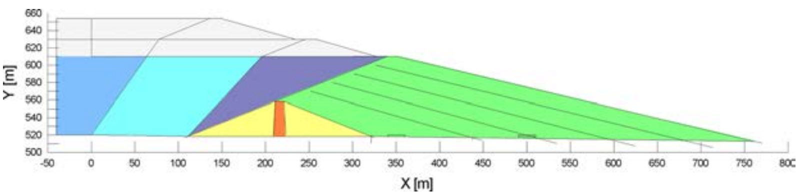

Fig. 4
Construction of tailings dam till elevation 610.0 masl, (I stage)
Construction d'un barrage de résidus jusqu'à une altitude de 610.0 masl, (stade I)

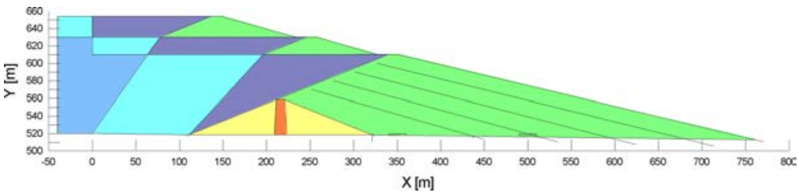

Fig. 5
Construction of tailings dam till elevation 630.0 masl, (II stage, phase 1)
Construction d'un barrage de stériles jusqu'à une altitude de 630,0 m (phase II, phase 1)

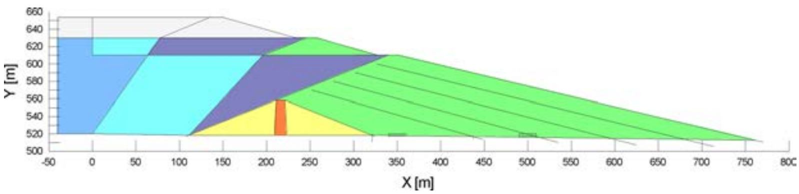

Fig. 6
Construction of tailings dam till elevation 654.0 masl, (II stage, phase 2)
Construction d'un barrage de stériles jusqu'à une altitude de 654,0 m (phase II, phase 2)

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 R. Macedonia. Namely, the highest conventional dam (for water reservoir), dam Kozyak, 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 geomechanical 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 of the 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 geostatic medium from interest in the analysis. In such a way is prepared idealized cross section for structural analysis, and the heterogeneous composition of the tailings dam is modeled with number of segments by 6 different materials, (fig. 6). The discretization of the tailings dam for static analysis (fig. 7) is done in order to model the initial (pre-earthquake) stage, and more realistic response at action of strong earthquakes to be obtained.

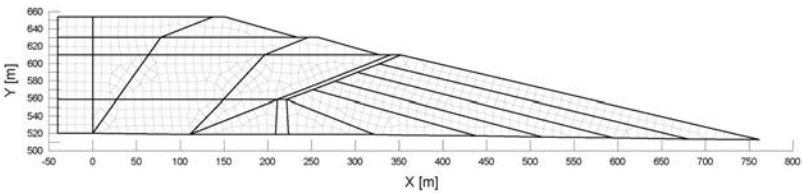

Fig. 7
Discretization of the medium for dynamic analysis with
FEM (N=804, E=769)
Discrétisation du milieu pour l'analyse dynamique avec
FEM (N = 804, E = 769)

3. SEISMIC PARAMETERS

The choice of the parameters for design earthquakes and adoption of the material dynamic parameters is taken over from the existing documentation. Having in consideration that the area of R. Macedonia is relatively good investigated from seismic aspect and also is performed geophysical testing on the existing tailings dam Topolnica, the seismic parameters were adopted based on the available data bases. The characteristics of the earthquake excitations are adopted by analysis of the following documentation [10, 11, 12, 13, 14, 15, 16]. The duration of the earthquake excitation is adopted rounded at ± 5 s, in dependence of PGA [17]. So, in the dynamic analysis, for earthquake Z1 with PGA1 = 0.26 g, duration is t1 = 20 s, while for earthquake Z2 with PGA2 = 0.40 g, the duration is adopted at t2 = 25 s. The vertical component of the acceleration from the seismic excitation is adopted at 2/3 from the horizontal component [18], apropos for earthquake Z1 corresponds value in vertical direction PGA1y=0.17 g, and for earthquake Z2 the appropriate value is PGA2y = 0.27 g. For full dynamic analysis in time domain is required knowing of the frequent composition of the design earthquakes for research of the seismic response of the tailings dam [19]. The actual ground excitations in for analysis of the dynamic response of tailings dam Topolnica are adopted as follows: (a) synthetic earthquake – Eurocode 8, type 1, fig. 8 and (b) realistic earthquake (appropriately scaled), Ulcinj – 1979, recorded in the Balkan region.

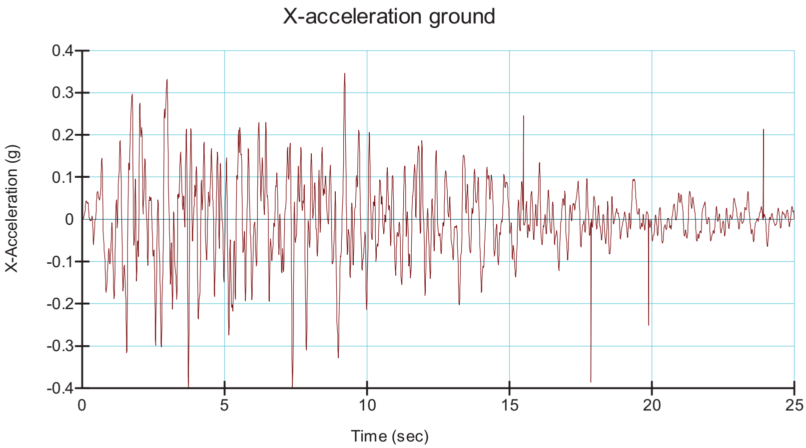

Fig. 8
Time history (accelerograph) of horizontal acceleration component for MCE/SSE earthquake Z2_EC8_1, t2 = 25 s, PGAx2 = 0.40 g и PGAy2 = 0.27 g (EuroCode8, type 1)
Chronologie (accélérographe) de la composante d'accélération horizontale pour le séisme MCE / Z Z2_EC8_1, t2 = 25 s, PGAx2 = 0,40 g P PGAy2 = 0,27 g (EuroCode8, type 1)

The values of the dynamic material parameters are chosen by study of the available documentation [20, 21]. The values for the non-linear dynamic parameters of the local materials (for ELA model) are assumed – according to the properties of the materials and experience dependences taken over from technical literature in field of geotechnical earthquake engineering – for dynamic testing of materials: sand, gravel, alluvia, crushed stone by the authors: Seed (1986), Idriss (1990), Vucetic and Dorby (1991), Kokusho (1980) and Tanaka (1987).

4. MATHEMATICAL MODEL FOR DYNAMIC ANALYSIS

In the model for dynamic analysis of fill dams in time domain is applied program QUAKE [22]. 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 mathematical model for response of the fill dam by linear constitutive laws (linear analysis and equivalent linear analysis and non-linear analysis are the first step of the dynamic analysis in time domain. Afterwards the results for the stresses during earthquake should be used in mathematical model for stability, in order to determine the dynamic stability and permanent deformations of the geotechnical structure.

The slopes sliding mechanism at fill dams is created from the increased shear stresses, generated by the dynamic inertial forces during the earthquake. If such shear stresses overcome the material shear resistance (for the typical sliding surfaces), then the stability factor of the potential sliding body obtains value lower then 1.0. But such values lower then 1.0, by extremely short durations (parts of second) does not mean slope full failure. It means that in such short intervals, in those zones are caused permanent deformations. The cumulative effect of such deformations is the permanent displacement of the potential sliding body during the seismic excitation that can be calculated by Newmark method [23]. The drawback of this method is that it is not favorable for relatively soft earth dams, by gentle slopes – adopted by condition for providing static stability, as for the case of tailings dam Topolnica [24].

The second approach for determination of the permanent deformations during the seismic excitation, not only for the potential sliding body, but in case of any node within the fill dam, is the method of Dynamic deformation analysis [25], applied in the present analysis. Such analysis in its basic is successive non-linear redistribution of the stresses and in the dynamic analysis of fill dams first was applied in the second decade of the 21st century.

By such method, for geomedium 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 one load case during the dam's dynamic response are produced elastic and eventual plastic strains. If dynamic inertial forces cause plastic strains then in the geomedium will occur permanent deformations. The permanent displacements at any point in the dam, at end of the seismic excitation are cumulative sum of the plastic deformations.

5. INITIAL (PRE-EARTHQAUKE) STRESS STATE

Critical state for assessment of the seismic resistance of the tailings dam no. 2-2 for crest elevation 654.0 masl is when the potential hazard of the hydro system regarding the downstream river valley is maximal. It is a case when the waste lagoon is at maximal operating level (or normal water level at elevation 652.0 masl) and when steady seepage in the tailings dam is established. Then are generated maximal values of the pore pressure (fig. 9) and the geomedium has minimal effective normal stresses (fig. 10) apropos it possesses minimal tangential resistance or reduced stiffness.

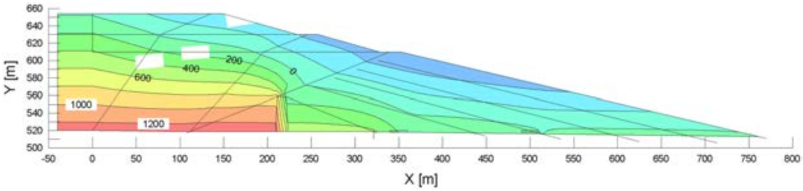

Fig. 9
Pore pressure distribution in kPa, for steady seepage in the tailings dam, at upper water elevation at 652.0 masl
Distribution de la pression interstitielle en kPa, pour un suintement stable dans la digue à stériles, à l'altitude supérieure de l'eau à 652.0 m

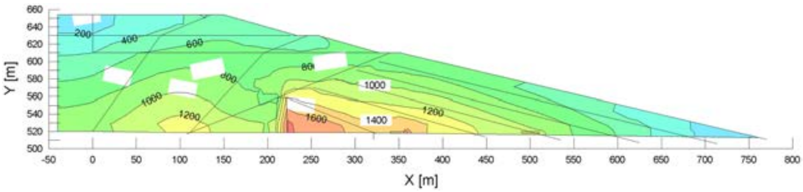

Fig. 10
Maximal effective stresses distribution, value of 1,890 kPa, for steady seepage in the tailings dam, at upper water elevation at 652.0 masl
Répartition efficace maximale des contraintes, valeur de 1 890 kPa, pour l'infiltration continue dans le barrage de résidus, à l'altitude de l'eau supérieure à 652.0 m

6. DAM RESPONSE AT ACTION OF MCE/SSE – CATASTROPHIC EARTHQUAKE

Here below is displayed the dam response at action of Maximum Credible Earthquake (MCE) or Safety Evaluation Earthquake (SEE) – earthquake Z2, by PGAx = 0.40 g and PGAy = 0.27 g. Such dynamic response is analyzed in the downstream edges of dam crest: dam no. 2-2 at elevation 654.0 masl, dam no. 2-1 at elevation 630.0 masl and dam no. 1 at elevation 610.0 masl. The permanent displacements, obtained by Dynamic deformation analysis (fig. 11, 12, 13 and 14), are key parameter for assessment of the seismic resistance of the fill dam, and are studied in the critical point from where is possible uncontrolled emptying of the lagoon – upstream edge of the dam no. 2-2 crest at elevation 654.0 masl. The dynamic stability of the dam was analyzed only for the downstream slope, critical in case of tailings dams. By application of the Newmark method it was confirmed that the dynamic stability of the dam is not endangered and that authoritative loading for choice of the downstream slope is the action of static loading.

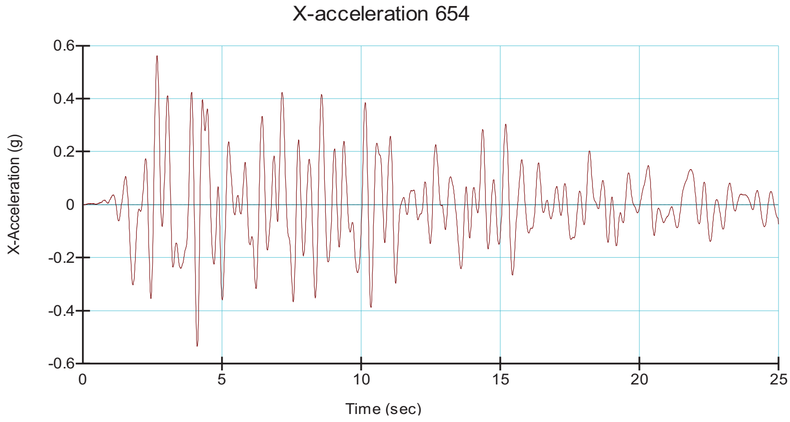

Fig. 11
Absolute accelerations a[g] ÷ t[s] in horizontal direction, dam. no. 2-2, elevation 654.0 masl, synthetic earthquake Z2 (EC8, type 1)
Accélérations absolues a [g] ÷ t [s] dans le sens horizontal, barrage. non. 2-2, élévation 654,0 m, tremblement de terre synthétique Z2 (EC8, type 1)

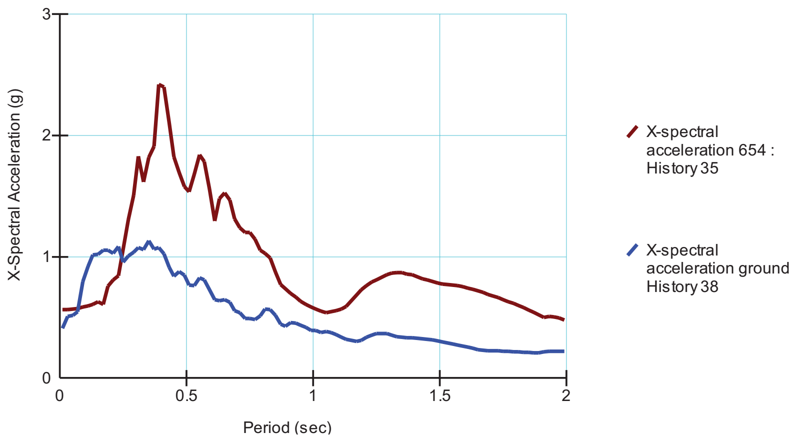

Fig. 12
Acceleration response spectra Sa [g] ÷ T [s] for DR = 0.05, in rock foundation (excitation) – synthetic earthquake Z2 (EC8, type 1) and at dam no. 2-2 crest (response)
Spectre de réponse d'accélération Sa [g] ÷ T [s] pour DR = 0,05, dans la fondation de la roche (excitation) – tremblement de terre synthétique Z2 (EC8, type 1) et au barrage no. 2-2 crête (réponse)

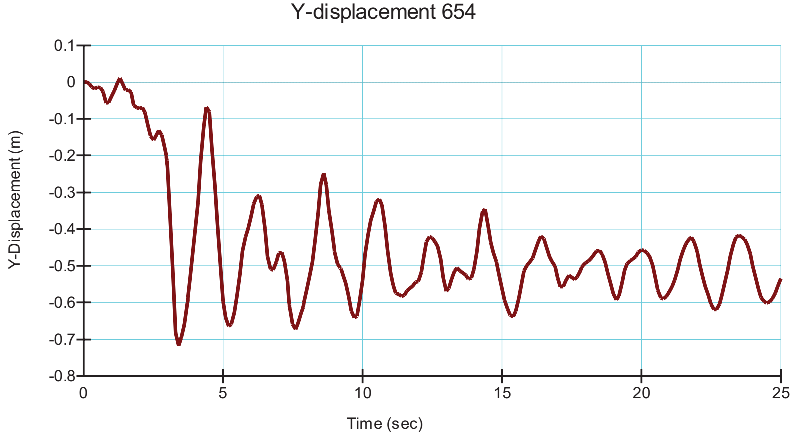

Fig. 13
Permanent vertical displacements by dynamic deformation method, Y[m] ÷ t[s], at the upstream edge of dam no. 2-2 crest, elevation 654.0 masl for synthetic earthquake Z2 (EC8, type 1)

Déplacements verticaux permanents par la méthode de déformation dynamique, Y [m] ÷ t [s], au bord amont du barrage no. 2-2 crête, élévation 654.0 msl pour tremblement de terre synthétique Z2 (EC8, type 1)

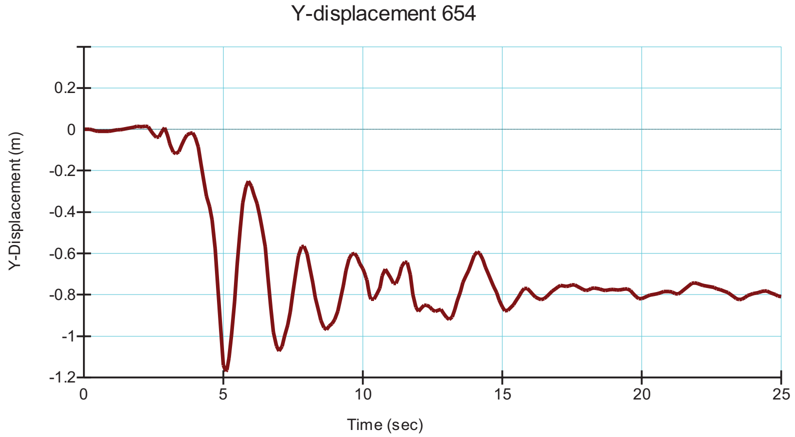

Fig. 14
Permanent vertical displacements by dynamic deformation method, Y[m] ÷ t[s], at the upstream edge of dam no. 2-2 crest, elevation 654.0 masl for realistic scaled earthquake Z2 (Albatros, 1979)

Déplacements verticaux permanents par la méthode de déformation dynamique, Y [m] ÷ t [s], au bord amont du barrage no. 2-2 crête, élévation 654,0 m pour le séisme réaliste Z2 (Albatros, 1979)

7. CONCLUSIONS

The validity of the dynamic analysis of the dam by mathematical model is verified by the following: (1) the diagrams of the time histories of the absolute accelerations and relative displacements in the dam crest have proper shape and distribution, appropriate for dynamic response of soft fill dams; (2) By analysis of the accelerations response spectra at dam crest at elevation 654.0 masl (for excitations levels OBE with 0.26 g and MCE with 0.40 g) it can be noticed that the zone of resonant effects is in the interval (0.5 ÷ 0.8) s, thus corresponding to the analytically calculated and recorded data for eigenvalues of such type of structures; (3) At action of OBE earthquake with PGA = 0.26 g, the dynamic amplification factor in the dam crest at 654.0 masl is DAF = (1.4-1.6), while in case of catastrophic MCE earthquakes with PGA = 0.40 g, is obtained DAF = (1.0-1.4). Such dam response is logical and it is due to the stiffness reduction and increase of the damping by rise of the non-linear deformations – proportional to the power of the earthquake excitation; (4) The dam crest response corresponds to the recorded data for the degree of dynamic amplification for such type of structures at action of strong earthquakes, apropos is the key indicator for the proper conducted dynamic analysis.

By application of the Dynamic deformation analysis for earthquakes with different frequent composition, are obtained permanent vertical displacements (settlements) in the crest at 654.0 masl, from Y = 48 cm in case of OBE till Y = 81 cm in case of MCE. From the recorded data for displacements at constructed tailings dams exposed at strong earthquakes it can be stated that for dam Topolnica, the calculated results by such method are more realistic then the results obtained by Newmark method. By such dynamic analysis is confirmed that the Newmark method is not suitable for relatively soft earth dams, with gentle slopes – adopted for requirements for satisfaction of the static stability.

The cumulative settlement in the crest at 654.0 masl, caused by catastrophic earthquake, are sum of: (1) additional compaction and reduced stiffness at materials on cyclic action Y1 = 70.0 cm (calculated by approximate approach), (2) dissipation of the pore excessive pressure caused by the liquefaction phenomena Y2 = 3.5 cm, (determined by other analysis), and (3) permanent displacements caused by dynamic inertial forces during earthquake Y3 = 81.0 cm (determined by the present analysis). The cumulative settlements in the crest at 654.0 masl are: Ys = Y1+Y2+Y3 = 70.0+3.5+81.0 = 154.5 cm. So the height of 2.0 m is not reached (from dam crest at 654.0 masl to the highest level of tailings sill in the lagoon 652.0 mnv), apropos there is no danger of rapid (uncontrolled) flow of sill from the waste lagoon during action of catastrophic earthquake.

REFERENCES

[1] PETKOVSKI L., TANČEV L., MITOVSKI S. A Contribution to the standardization of the modern approach to assessment of structural safety of embankment

dams", 75th ICOLD Annual Meeting, International Symposium "Dam Safety Management, Role of State, Private Companies and Public in Designing, Constructing and Operation of Large Dams", St.Petersbourg, Russia, 2007.

[2] PETKOVSKI L., MITOVSKI S. Creating of tailings space by stage construction of rockfill dam, 25. Congress on Large Dams, ICOLD, Stavanger, Norway, 2015.

[3] ICOLD, Bulletin 45, Manual on tailings dams and dumps, 1982.

[4] ICOLD, Bulletin 139, Improving tailings dam safety – Critical aspects of management, design, operation and closure, 2011.

[5] PETKOVSKI L. Modified conventional dam in phase construction – an alternative to tailings dam, UDK: 627.821, Original scientific paper, Watereconomy, ISSN 0350-0519, Vol. 47, No. 273-275, p. 41-50, Beograd, Serbia, 2015;

[6] PETKOVSKI L., MITOVSKI S. Comparison Of Tailings Dams Dynamic Response In Case Of Central And Downstream Method Of Construction, 82. Annual Meeting of ICOLD, International Symposium: Dams in Global Environmental Challenges, Bali, Indonesia, 2014.

[7] PETKOVSKI L., MITOVSKI S. Structural safety of tailings dams at increasing of the deposit space, Conference, Talinigs dams in Republic of Macedonia, MACOLD, Shtip, R.Macedonia, 2012

[8] PETKOVSKI L. Static and dynamic stability of tailings dams at heightening", Journal Pressing, Volume 2, no.12, ISSN 1857-7-44X, 2012.

[9] PETKOVSKI L., Ilievska F. ESTIMATION OF HYDRO TAILING'S DYNAMIC RESPONSE DURING THE INFLUENCE OF STRONG EARTHQUAKES, III Symposium of MAG, Struga, 2010.

[10] PASKALOV T., ZELENOVI V., "Rules on technical norms for design and calculation of engineering facilities in seismic areas", Federal Institute for Standardization – Beograd, 1986.

[11] MANIĆ M. A new site dependent attenuation model for prediction of peak horizontal acceleration in Northwestern Balkan, 11th European Conference on Earthquake Engineering, Balkema, Rotterdam, 1998.

[12] ICOLD, Bulletin 148, Selecting seismic parameters for large dams – Guidelines (revision of Bulletin 72), 2016.

[13] WIELAND M., Seismic Aspects of Dams, General Report of Question 83, ICOLD, Montreal, Canada, 2003.

[14] SKOKO D., ARSOVSKI M., HADZIEVSKI D. Determination of Possible Earthquake Origin Zones of the Territory of Yugoslavia, UNDP/UNESCO, Survey of the Seismicity of the Balkan Region, UNESCO – Skopje, 1974.

[15] Eurocode 8, Design of structures for earthquake resistance, Doc CEN/TC250/SC8/N335, DRAFT No 6, Brussels, 2003.

[16] SIMQKE Manual of computer program for simulation of acceleration time-history of synthetic earthquakes from target response spectrum, 1997.

[17] AMBERG W., BOSSONEY C., DARBRE G.R., HAMMER J., OTTO B., STUDER J., WIELAND M Swiss guidelines on the assessment of the earthquake behaviour of dams, 12th European Conference on Earthquake Engineering, London, 2002.

[18] ICOLD, Bulletin 72, Selecting seismic parameters for large dams – Guidelines, 1989.

[19] WIELAND M. review of seismic design criteria of large concrete and embankment dams, 73rd Annual Meeting of ICOLD, Tehran, IRAN, 2005.

[20] IZIIS – Skopje, Dynamic laboratory testing of the material from tailings dam Topolnica, of the copper mine “Bucim” – Radovish, K. Talaganov and other, 2001.

[21] KRAMER S.L., Geotechnical Earthquake Engineering, Prentice Hall, New Jersey, USA, 1996.

[22] Geo-Slope QUAKE/W “Dynamic modeling”, GEO-SLOPE International Ltd., Calgary, Alberta, Canada, 2013.

[23] Geo-Slope SLOPE/W “Stability analysis”, GEO-SLOPE International Ltd., Calgary, Alberta, Canada, 2013.

[24] PETKOVSKI L., ILIEVSKA F. Comparison of Different Advanced Methods for Determination of Permanent Displacements of Tailings Dams in Earthquake Condition“, 14th Europian Conference on Earthquake Engineering, Ohrid, R.Macedonia, 2010.

[25] Geo-Slope SIGMA/W “Stress/deformation analysis”, GEO-SLOPE International Ltd., Calgary, Alberta, Canada, 2013.