Determination of the stability coefficient of the slopes of earth dams by dynamic and pseudo-static methods

Détermination du coefficient de stabilité des pentes des barrages en terre par des méthodes dynamiques et pseudo-statiques

Anastasiya Almakaeva & Armen Ter-Martirosian
Moscow State (National Research) University of Civil Engineering, Russia, totilas96@mail.ru

ABSTRACT: The article discusses the stability of earthmen dams after seismic action given by dynamic and pseudo-static methods. The purpose of this study is to determine the most correct method for modeling seismic impact in numerical simulation and calculation the stability of earthmen dams based on a comparison of different methods of calculating the stability of slopes. Using numerical modeling by software package PLAXIS 2D the influence of the method of setting the seismic impact on the stability coefficient of the dam slopes was considered. The dynamic method provides the assessment of the stress-strain state and the stability of dams based on accelerograms as a function of the dependence of accelerations on time. The pseudostatic method is based on applying maximum acceleration to the centers of mass of finite elements in order to increase the resulting force. There is discussing the impact of the static and dynamic characteristics of soils and the type of drained and non-drained soil behavior on stability. As dynamic calculation takes a rather large amount of time there was studied how the dynamic calculation affects the stability coefficient based on the full accelerogram and part of it where the peak acceleration values were reached.

RÉSUMÉ : L'article traite de la stabilité des barrages terrestres après une action sismique donnée par des méthodes dynamiques et pseudo-statiques. Le but de cette étude est de déterminer la méthode la plus correcte pour modéliser l'impact sismique en simulation numérique et calculer la stabilité des barrages terrestres en se basant sur une comparaison des différentes méthodes de calcul de la stabilité des pentes. En utilisant la modélisation numérique par le progiciel PLAXIS 2D, l'influence de la méthode de réglage de l'impact sismique sur le coefficient de stabilité des pentes du barrage a été considérée. La méthode dynamique permet d'évaluer l'état contrainte-déformation et la stabilité des barrages à partir d'accélérogrammes en fonction de la dépendance des accélérations au temps. La méthode pseudo-statique est basée sur l'application d'une accélération maximale aux centres de masse des éléments finis afin d'augmenter la force résultante. On discute de l'impact des caractéristiques statiques et dynamiques des sols et du type de comportement des sols drainés et non drainés sur la stabilité. Comme le calcul dynamique prend beaucoup de temps, il a été étudié comment le calcul dynamique affecte le coefficient de stabilité basé sur l'accélérogramme complet et une partie de celui-ci où les valeurs d'accélération de pointe ont été atteintes.

KEYWORDS: stability coefficient, earth dam, numerical simulation, dynamic method, pseudo-static method.

1 INTRODUCTION

One of the most difficult issues in hydraulic engineering is the issue of determining the stability after seismic impact. It is connected to the complexity of the application of seismic load and the description of the elastic-visco-plastic behavior of soils under seismic impact. Hydraulic structures are important objects in the energy industry, agriculture, water supply and other spheres of human life. Hydraulic structures include earth dams that retain large volumes of water and form reservoirs. The destruction of such grandiose structures can be accompanied by an outbreak of the dam and, therefore, it can create huge damage to the population, economy and ecology of the country. To eliminate the disaster, large human and financial resources are required. In addition, it can take months or even years to repair the effects of earthquake and flood damage and restore hydraulic structures to operational condition. Therefore, the calculations of seismic impact of hydraulic structures should be given special attention.

The problem of seismic impact of structures is solved in 2 stages: determination of the stress-strain state (SSS) of an earth dam after seismic impact and calculation of the stability of its slopes. According to EN 1998-1: 2004 (Eurocode 8: Design of structures for earthquake resistance) the first task can be solved by 4 methods: lateral force method of analysis, modal response spectrum analysis, non-linear static (pushover) analysis, non-linear time history (dynamic) analysis. Three of the listed methods are used to calculate the seismic resistance of hydraulic structures, including for earth dams, in accordance with Russian regulatory documents (SP 358.1325800.2017; Metodicheskoye posobiye, 2016). These three methods will be discussed below.

The first calculation method is carried out according to the static theory (ST) where seismic loads are determined by multiplying the mass of the soil volume by its absolute acceleration. Nimbalkar S. and Choudhury D. (Nimbalkar S.S. and Choudhury D. 2010) were engaged in the solution the problem of seismic impact according to the static theory for the bund wall. They concluded that this method is too conservative (simplified) and gives an approximate estimate of the current accelerations in the body of the dam, since it does not take into account either the influence of time, or the frequency of vibrations, or the properties of soils.

The second calculation method is based on the dynamic theory (DT) in which the seismic impact is created in the form of accelerograms of soil vibrations by numerically integrating the equations of motion. For calculations, two horizontal and one vertical accelerograms should be used. Also, it should take into account the dynamic deformation and strength characteristics of soils and the damping properties of soils. Velocigrams and seismograms of soil motion can also be used to calculate the seismic impact. Chakraborty D. and Choudhury D. were engaged in calculations of seismic impact of a hydraulic structure according to the dynamic theory (Chakraborty D. and Choudhury D. 2013). They determined the stability of the bund wall after seismic impact, which was applied by static and dynamic methods. The calculation results showed that the dynamic calculation gives the stability coefficients lower because this method takes into account duration, frequency, inertia forces and many other factors, while static calculation takes into account only accelerations that are constant during the calculation. In another work accelerations and shear deformations were determined that occurred in the body of an earth dam in three different software packages using a dynamic method for calculating seismic impact (Castellia F., Lentinia V. and Trifaròa C. A. 2016). They got good convergence of results.

The calculation of the seismic impact of a hydraulic structure according to the third calculation method is based on the linear spectral theory (LST), in which the values of seismic loads are determined by the dynamics coefficients or by the response spectra depending on the frequencies and modes of natural vibrations. According to the regulatory documents (SP 358.1325800.2017), the number of natural vibration modes taken into account in the calculations should not be less than 25. Seismic acceleration is a vector constant in time, the modulus of which is equal to the peak acceleration, which is calculated based on the initial seismicity, calculated seismicity and real soil conditions. The direction of the seismic impact should be chosen so that it has the worst impact on the structure. The study of the linear-spectral theory was carried out by the authors of Bestuzheva A.S. and Nguyen F.L. (Bestuzheva A.S. and Nguyen F.L. 2010) who compared the seismic forces obtained by dynamic and linear spectral methods and analyzed the influence of various factors on them. They concluded that for the calculation of the seismic force using the LST and the real accelerogram, the seismic force will be half as much if the vibration damping is taken into account. The calculation of the seismic force according to the dynamic theory showed similar results, but the values of the seismic forces turned out to be several times less than in the calculation according to the LST. That is, the accuracy of calculation by spectral methods decreases for three-dimensional problems with unevenly distributed mass and stiffness. In addition, the authors studied the effect of the number of natural vibration modes on the seismic force and concluded that in order to achieve the required accuracy, it is recommended to use at least 30 natural vibration modes.

The influence of natural vibrations of a structure on its seismic resistance is shown in study (Zaretskii Yu. K., Groshev M. E. and Olimpiev D. N. 1992). Authors Zaretsky Yu., Groshev M. and Olimpiev D., in accordance with the dynamic theory, calculated the seismic resistance of the Rogun hydroelectric power station using various accelerograms. As a result, an accelerogram with a lower peak acceleration of 0.2g was found to be more critical than an accelerogram with a peak acceleration of 0.4g. Thus, it can be concluded that the worst effect on the seismic resistance of a structure is made by the forced vibrations entering into resonance with the natural vibrations of the system.

The most common method for calculating stability in engineering practice is the method of slices and its various interpretations. In the general case, this method does not take into account the relationship between the stress-strain state and the calculation of stability, because these calculations have different prerequisites and are performed separately from each other. Therefore, the authors Sainov M., Kudryavtsev G. and Gapeev D. developed a special computational program Otkos_N which allows calculating the stability taking into account the stress distribution (Sainov M.P., Gapeev D.S. and Kudryavtsev G.M. 2017). The results of calculations for an earth-and-rockfill dam showed that for the calculation of the basic load combination, the stability will be higher than for using the method of slices. However, for the calculation for a special load combination (taking into account the seismic effect), a decrease of the stability of the upstream slope was determined, and at high seismic loads it can be expected that the stability coefficient may be lower than the standard.

Various authors have dealt with the relationship between the stress-strain state and the loss of stability (Zaretsky Yu.K. and Lombardo V.N. 1983; Rasskazov L.N. and Bestuzheva A.S. 1992; Ruan Y., Shi B., Yang J. and Peng S. 2019). Numerical calculation methods show that after an earthquake in the body of the dam, residual plastic deformations of the soil occur, which lead to local destruction and zones of the limiting state of the soil. Therefore, for the calculation of stability by the *«φ-c reduction»* method, destruction will occur faster, and, therefore, the stability coefficient will be lower than before the application of seismic impact.

In addition to changing the stress-strain state during an earthquake, it is necessary to take into account a number of other factors that can affect the seismic resistance of hydraulic structures. For example, under seismic impact an increase in pore pressure is observed which unloads the soil skeleton at the base and body of the dam which leads to a decrease of the stability coefficient (Orekhov V.V. 2015; Jin, J., Song, C., Liang, B. et al. 20). In world practice the issues of the influence of the mass of attached water on the change of the number and forms of natural vibrations and taking into account of the influence of tensile stresses on the stability of slopes have been poorly studied, although a number of studies show the need for further study of these problems (Bestuzheva A. and Kulyabin G. 2020; Lv G., He Y . and Wei B. 2020).

2 MATERIALS AND RESULTS

In this article, calculations of the seismic impact of the bund wall are carried out by numerical methods in a two-dimensional formulation in the geotechnical software package PLAXIS 2D. This program allows to carry out a dynamic calculation by two ways: a dynamic method and a pseudo-static method.

2.1 *Pseudo-static method*

In the first method the dynamic impact is modeled using the prescribed displacement as a function of time or using a dynamic load. The applied dynamic impact is the multiplication of the input value of static displacement or static load by the corresponding dynamic coefficient which can be represented by an accelerogram, velocigram, seismogram or a graph of the load versus time. Static components of displacement or load should be taken equal to one. Modeling the seismic impact is possible only with the prescribed displacement, which is applied to the bottom of the computational model. Dynamic load is used to describe the dynamic impact from moving vehicles, machinery and other structures and mechanisms that create dynamic vibrations. This method is based on the dynamic theory of calculating the seismic resistance of the hydraulic structures.

2.2 *Dynamic method*

The second method is based on the application of accelerations in fractions of the gravitational acceleration *g* in all directions of the axes at the points of the centers of gravity of the finite elements. The applied accelerations are determined based on the accelerograms. This method does not consider seismic impact as a process in time. In addition, it is important to note that the application of acceleration is carried out immediately to the entire model. Therefore it is applied only to simulate an earthquake and cannot be applied to simulate the dynamic effects of a moving vehicle or machinery. This method is based on the static theory of calculating the seismic resistance of the hydraulic structures.

2.3 *Calculation of stability*

The calculation of stability in the geotechnical software package PLAXIS 2D is carried out according to the *«φ-c* *reduction»* method. This method consists in a gradual decrease of strength characteristics until failure occurs. The stability coefficient is defined as the ratio of the actual strength characteristics to the corresponding characteristics at the moment of destruction.

2.4 *Description of the earth dam*

The study of pseudo-static and dynamic methods for calculating seismic resistance, as well as the study of the influence of the direction of action of seismic impact, damping properties of soils, excess pore pressure and natural vibrations of the system on seismic resistance were carried out for the bund wall. Design scheme of the problem in a two-dimensional formulation is shown in Figure 1.

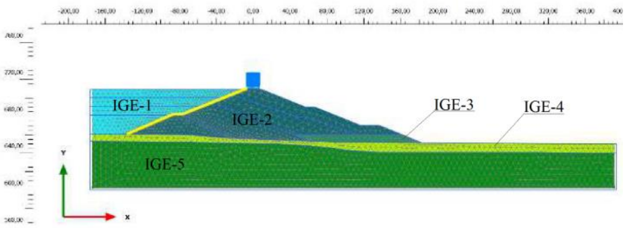

Figure 1. Design scheme of the bund wall

In accordance with Russian regulatory documents this structure belongs to the most dangerous category (category I) of hydraulic structures which is assigned depending on the type of dam and its height. The seismicity with a recurrence rate of 1 time in 5000 years is 8 points on the 12-point scale of the intensity of earthquakes of the Medvedev - Sponheuer - Karnik (MSK-64) (Sponheuer W. and Bormann P. 1981). Natural vibrations of the system can either be in resonance with forced vibrations and increase the amplitude of vibrations or damp them. The calculated accelerograms were obtained on the basis of actual earthquakes that occurred in the considered territory. The recorded accelerograms contain both forced and natural vibrations. In the calculation by the pseudo-static method the maximum accelerations were applied to the calculation model in all directions of the axes. Figure 2 shows the calculated accelerograms in fractions of *g* acting in two mutually perpendicular directions: in the horizontal direction and in the vertical direction.

The soil model is described by an elastic-ideal-plastic model with the Coulomb-Mohr strength criterion. The dam body consists of very coarse soil represented by coal shale (IGE-2), at the base there is a layer of loamy soil (IGE-4) with a thickness of 10 m underlain by a solid rock base (IGE-5). The calculations of seismic resistance were carried out taking into account the damping properties of soils which dampen vibrations due to the dissipation of kinetic energy. Table 1 shows the physical characteristics of soils and table 2 shows the strength and deformation characteristics of soils. In addition, damping characteristics from an analogue object were adopted for soils.

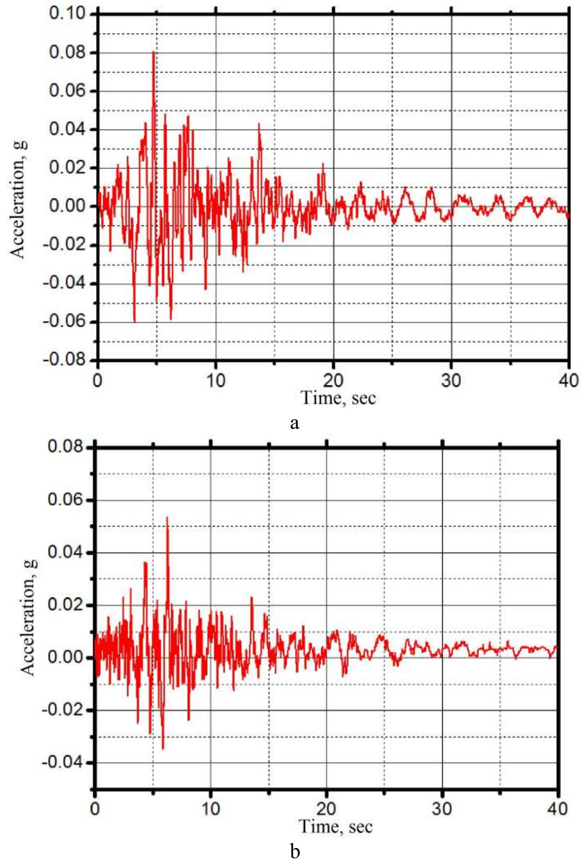

Figure 2. Calculated accelerograms acting: (a) - along the *X*-axis and (b) - along the *Y*-axis

Table 1. Physical characteristics of soils.

Soil	*Relative density,* $\gamma_{sat}/\gamma_{unsat,}$ *[kN/m³]*	*Coefficient of permeability,* κ_x/κ_y, *[m/day]*
IGE-1	19.4/19.5	0.00001/0.00001
IGE-2	20.5/22.5	15.0/15.0
IGE-3	21.0/23.5	15.0/15.0
IGE-4	20.3/21.2	0.00001/0.00001
IGE-5	26.7/27.1	15.0/15.0

Table 2. Strength and deformation characteristics of soils.

Soil	*Modulus of deformation, E, [MPa]*	*Cohesion, C, [kN/β²]*	*Internal friction angle, φ, [°]*
IGE-1	7.8	21.0	19.5
IGE-2	40.0	42.3	33.2
IGE-3	79.6	79.4	36.0
IGE-4	22.7	27.8	20.8
IGE -5	82.5	77.0	34.0

2.5 *Description of calculations*

In order to identify the worst influence of the directions of the action of accelerations from the point of view of seismic resistance calculations were carried out by the pseudo-static method for four different directions. Similar calculations to identify the worst influence of the direction of action of the accelerograms were carried out to determine the seismic resistance by the dynamic calculation method.

It is known that the strongest earthquake shock occur in the first 5-10 seconds after that the vibrations are attenuated. At the same time for the formation of slip planes and the occurrence of fracture as a result of shear time is required from several seconds to several minutes so all dynamic calculations were carried out for a full accelerogram until its complete attenuation. The duration of accelerograms is 40 seconds. However it is erroneously believed that the lowest stability of the earth dam slopes occurs at the moment of the greatest amplitudes of earthquake vibrations. Therefore, additionally the seismic resistance of the bund wall was determined at the time of the peak vibrations of the calculated accelerograms.

During an earthquake the soils have undrained behavior and the excess pore pressure increases. The result is the destruction of the soil. Therefore, to assess the impact without taking into account the excess pore pressure an additional calculation was carried out by the dynamic method with the drained behavior of soils. Besides this, a calculation was carried out without the damping properties of soils in order to assess their positive effect on the stability of the structure.

2.6 *Calculation results*

The calculation results showed that the stability of the slopes of the bund wall before seismic impact is 1.743. Figure 3 shows a slip prism before an earthquake.

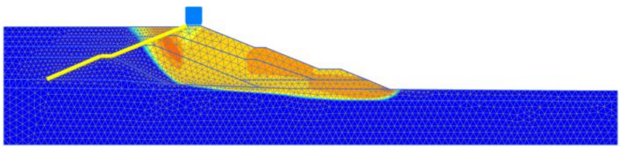

Figure 3. Sliding triangle of the bund wall before seismic impact with stability factor 1.743

After the application of seismic impact which was calculated by the pseudostatic method the stability coefficient changed depending on the direction of application of accelerations. The smallest stability coefficient is 1.244 at x = -1 and y = -1 and the largest at x = 1 and y = - 1 and is equal to 2.580. Thus, it is important to take into account the configuration of the design model and apply accelerations so that they increase the overturning moment and not the sum of the resisting moments.

Calculations of seismic resistance by the dynamic method for the full accelerogram taking into account the damping characteristics and undrained behavior of soils showed that the stability coefficient also depends on the direction of application of the calculated accelerograms although the range of values of the stability coefficient turned out to be smaller compared to the previous method. For the design case when the accelerograms were applied in the direction x = -1 and y = -1 the stability coefficient was equal to 1.531. This direction of vibration is also the worst. The highest stability coefficient turned out to be equal to 1.841 at x = 1 and y = 1. The different principle of application of seismic impact leads not only to a change of the value of the stability coefficient but also to a change in its values depending on the direction of the seismic impact.

Without taking into account the damping characteristics the stability coefficient decreases from 1.531 to 1.464. It indicates a positive effect on seismic resistance because they dampen vibrations and reduce soil deformations. Therefore it is recommended to take into account the damping characteristics of soils. They must be determined empirically for each engineering-geological element separately because they contribute to the determination of a more accurate stability coefficient. In some situations the damping properties of soils can even be of great importance for choosing the angle of the slopes of the earth dams if the calculated stability coefficient may be lower than the standard.

Evaluation of seismic resistance at the time of peak vibrations showed that the stability coefficient of the bund wall is 1.727 that practically does not differ from the stability before an earthquake. There are no plastic zones (destruction) of the soil (Figure 4) while when calculated for the full accelerogram both in the body of the dam and at its base extensive plastic zones of the soil are formed (Figure 5).

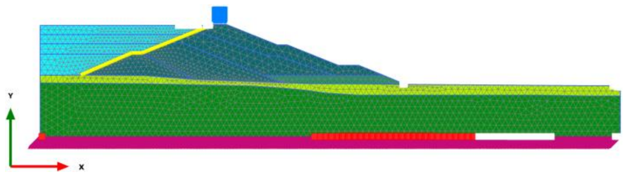

Figure 4. Plastic zones of the soil at the time of the action of peak vibrations

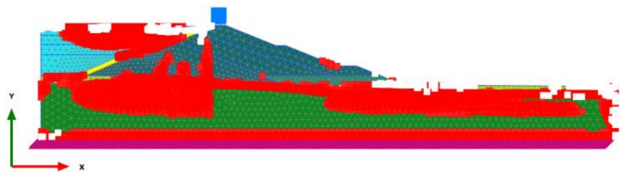

Figure 5. Plastic zones of soil after an earthquake

Consequently, due to the accumulated plastic deformations shear occurs faster and the stability coefficient is lower. The obtained results showed that the calculation of the full accelerogram can most accurately correspond to the real picture of soil destruction under seismic impact. This also allows to get a more correct stability coefficient and take into account the natural vibrations of the structure.

During the calculations of seismic resistance by the dynamic method with the drained behavior of soils excessive pore pressure does not arise at the base and body of the dam. In this case, the stability coefficient turned out to be equal to 1.727 i.e. practically equal to the coefficient of stability before seismic impact. During the calculation with undrained soil behavior excess pore pressure grows and accumulates. It leads to the formation of additional plastic zones of soil destruction and a significant change of the stress state of soils (Figure 6).

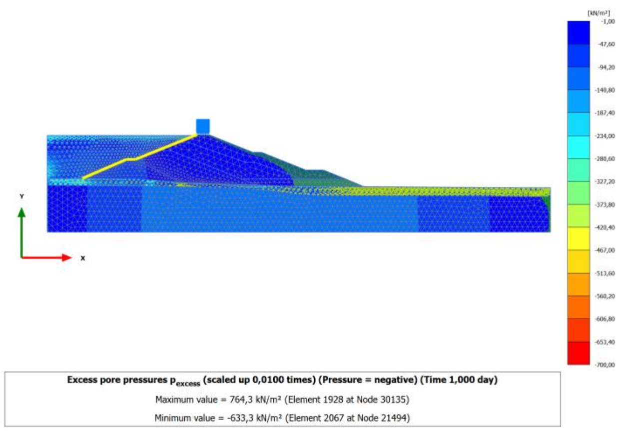

Figure 6. Isofields of excess pore pressure after an earthquake

The obtained values of the stability coefficient for all considered design cases are summarized in Table 3.

Table 3. Summary table of standard and calculated stability factors.

Design case	*Stability coefficient*
Before seismic impact	1.743
Pseudo-static method:	
– $x = -1, y = -1$	1.244
– $x = 1, y = -1$	2.580
– $x = -1, y = 1$	1.260
– $x = 1, y = 1$	2.430
Dynamic method:	
– $x = -1, y = -1$	1.531
– drained	1.727
– no damping	1.464
– before peak vibrations	1.763
– $x = 1, y = -1$	1.582
– $x = -1, y = 1$	1.824
– $x = 1, y = 1$	1.841

3 CONCLUSIONS

Comparing the pseudo-static method and the dynamic method it can be concluded that the dynamic method is more preferable because it allows to take into account many factors and recreate a more real stress-strain state during seismic action. The pseudo-static method is a simplified method. It does not depend on time and in this case the stability coefficient depends only on the applied accelerations and their direction of action. Therefore, this method is not applicable to structures of I and II structure category of hydraulic structures.

The dynamic method proceeds in time and allows one to take into account the nonlinear and damping properties of soils, the type of their drainage, natural vibrations of the structure, the period and frequency of forced vibrations, the duration of accelerograms, the direction of their application, excess pore pressures and changes in the stress-strain state of the soil mass. It makes this method suitable for calculating the seismic resistance of structures of any structure category.

In this calculation method the stability coefficient is also sensitive to the direction of action of the calculated accelerograms, moreover, the calculation for the full accelerogram allows to take into account the forced and natural vibrations of the structure. It is important to note that at the moment of peak vibrations of the seismic impact stability cannot significantly decrease or even not decrease at all as in the presented calculations. Because it takes time for the formation of shear planes and destruction but the strongest vibrations occur in the first 5-10 seconds of an earthquake. In addition, the calculations showed how the excess pore pressures and damping properties of soils strongly influence the change in stress-strain state and the stability coefficient. Therefore, using the dynamic method it is recommended to calculate the full accelerogram taking into account the undrained behavior and damping properties of soils.

The dynamic method is a complex method that requires further study and verification of the results obtained for other configurations and types of dams. Therefore, further research in this direction is planned.

4 REFERENCES

Bestuzheva A. and Kulyabin G. 2020. Forms of natural vibrations of a gravitational dam on an elastic foundation, taking into account the attached mass of water. *IOP Conference Series: Materials Science and Engineering* 883.

Bestuzheva A.S. and Nguyen F.L. 2010. Dinamicheskiy i spektral'nyy metody opredeleniya seysmicheskoy nagruzki, deystvuyushchey na sooruzheniye pri zemletryasenii. *Vestnik MGSU* 1, 155-168.

Castellia F., Lentinia V. and Trifaròa C. A. 2016. 1D seismic analysis of earth dams: the example of the Lentini site. *Procedia engineering* 158, 356-361.

Chakraborty D. and Choudhury D. 2013. Pseudo-static and pseudo-dynamic stability analysis of tailings dam under seismic conditions. *Proceedings of the National Academy of Sciences, India Section A: Physical Sciences* 83, 63-71.

EN 1998-1: 2004. Eurocode 8: Design of structures for earthquake resistance.

Jin, J., Song, C., Liang, B. et al. 2018. Dynamic characteristics of tailings reservoir under seismic load. *Environmental Earth Sciences* 77.

Lv G., He Y. and Wei B. 2020. Dynamic Stability Analysis of Slope Subjected to Surcharge Load considering Tensile Strength Cut-Off. *Mathematical Problems in Engineering* 2020.

Metodicheskoye posobiye, Rukovodstvo po uchetu seysmicheskikh vozdeystviy pri proyektirovanii gidrotekhnicheskikh sooruzheniy, 2016.

Nimbalkar S.S. and Choudhury D. 2010. Effect of Amplification on Seismic Stability of Tailings Dam. *Soil Dynamics and Earthquake Engineering*.

Orekhov V.V. 2015. Issledovaniye napryazhenno-deformirovannogo sostoyaniya i ustoychivosti kamenno-nabrosnoy damby pri seysmicheskom vozdeystvii. *Vestnik MGSU* 11, 157-166.

Rasskazov L.N. and Bestuzheva A.S. 1992. Seismic stability of earth dams. *Hydrotechnical Construction* 26 (2), 91-99.

Ruan Y., Shi B., Yang J. and Peng S. 2019. The Slope Stability Analysis Under the Coupling Effect of Earthquake and Rainfall. *Proceedings of the 8th International Congress on Environmental Geotechnics (ICEG)* 3, 497-506.

Sainov M.P., Gapeev D.S. and Kudryavtsev G.M. 2017. Vliyaniye napryazhonnogo sostoyaniya kamenno-zemlyanoy plotiny na ustoychivost' yeyo otkosov. Internet-zhurnal «NAUKOVEDENIYE» 9(6).

SP 358.1325800.2017 Hydraulic structures. Rules of design and construction in seismic-prone regions.

Sponheuer, W.; Bormann, P. 1981. Introduction to the up-dating of the seismic scale MSK-64. *Gerlands Beitrage zur Geophysik* 90, 213-216.

Zaretskii Yu. K., Groshev M. E. and Olimpiev D. N. 1992. Development of methods for evaluating the earthquake resistance of earth dams. *Soil Mechanics and Foundation Engineering* 29, 179–186.

Zaretsky Yu.K. and Lombardo V.N. 1983. Statics and dynamics of earth dams.