Comparative analysis of calculation methods seismic impact and influence of methods on the safety factor for hydraulic structures

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Abstract. Rasskazov L.N., Bestuzheva A.S., Sainov M.P., Chernysh A.S., Francesco Castelli and many others were engaged in studies of the stability of slopes under seismic impact. The paper considers numerical methods for assessing the seismic stability of embankment dams in flat and three-dimensional problems in two ways: a direct dynamic method and a pseudostatic method. Several simulation cases are considered in a flat problem on a test problem using soil properties taken from a real site of an operating hydroelectric power plant. During the simulation, the following main simulation cases were considered: the natural stability; calculation without static components; calculation with static components; impact of free vibrations; calculation with full accelerogram; calculation with static deformation properties of soils; calculation with dynamic deformation properties of soils; calculation with undrained strength of soils; pseudostatic method. The analysis of the results showed that the calculation of the seismic stability of an embankment dam by the direct dynamic method gives the results that are closest to reality, in contrast to the pseudostatic calculation method.

1. Introduction

Hydraulic structures of various classes and purposes are important objects in the national-economic sphere, in the energy and metallurgical industry, in agriculture, in the water transport system, fisheries, water-supply, sewerage, hydromelioration and other sectors of the economy. The structure of hydraulic structures includes an embankment dam and dams, which allow holding huge volumes of water masses, thereby forming reservoirs. They are the main type of retaining structure. Basically, they are being erected in areas with high seismic activity, therefore, ensuring the seismic resistance of an embankment dam is an urgent problem. The calculations of stability due to seismic effects should be given great attention, since an earthquake can cause colossal damage to the population, economy and ecology of the country, and taking into account the flooding due to a dam break, the scale of the catastrophe increases several times. In addition, it will require large human and financial resources and time to eliminate the consequences of earthquakes and floods.

Decrease in the stability of the slopes of an embankment dam after seismic impact is a problem that is increasingly faced by designers and builders. Many works are devoted to the study of the stress-strain state of an embankment dam erected in areas of seismic activity, in which the authors describe various methods and approaches to calculating the stability of slopes under the action of a seismic
load. Rasskazov and Bestuzheva proposed an improved method for determining the seismic resistance of embankment dams, based on the method of "energy soil model", which considers the elastic-visco-plastic behavior of the soil under load [1]. Barkov and Bestuzheva in their work, they determined the periods and natural mode shapes of the dam, taking into account the elastic properties of the foundation, and also evaluated the contribution of each natural mode shape to the magnitude of the seismic force [2]. Bestuzheva in her work [3] performed a comparison of seismic forces and accelerations obtained by different spectral methods. Stainov, Gapeev and Kudryavtsev conducted a study of the influence of the stress state of the dam on the safety factor of its slopes with the basic and special loads combination [4]. Cascone and Rampello in their work evaluated the stability of an embankment dam using accelerograms. For the calculation, ten artificial and five real accelerograms were taken [5]. Psarropoulos and Tsompanakisa investigated the behavior and stability of the bund wall under static and dynamic loading using numerical simulations in a two-dimensional problem [6]. During an earthquake, the physical and mechanical properties of soils change, excessive pore pressure appears, residual deformations and other factors that reduce stability and contribute to the formation of shear planes [7,8]. Heavy precipitation and earthquakes are the main reasons for the decrease in the stability of the slopes of an embankment dams. Yongfen Ruan et al. analyzed excess pore pressure and slope safety factor at different earthquake intensities [9]. The results of their study showed that after an earthquake, residual deformations occur in the soil, which reduce the stability of slopes. Zhongchang Wang and Bo Li in their study determined the stresses and displacements of structures of a hydraulic structure during seismic impact. They concluded that the maximum values of stresses and strains occur at the time of peak fluctuations [10]. Luzhao Dan, Ming Tian and others have considered methods of increasing the stability of slopes due to the negative impact of seismic waves in a three-dimensional problem [11]. Bestuzheva and Nguyen conducted a comparative analysis of two methods for determining the seismic load: dynamic and spectral methods [12]. Francesco Castelli and others [13] presented the results of a one-dimensional analysis of the dynamic behavior of the embankment dam. A real seismogram obtained in 1990 after the earthquake in Saint Lucia was used to simulate the seismic impact. Jiaxu Jin, Chenguang Song and others investigated the stability of the bund wall under seismic loading [14]. To study the dynamic characteristics of the bund wall, experimental tests were carried out on a vibrating table. The correctness of bund wall model was verified by numerical calculations. Debarghya Chakraborty and Deepankar Choudhury performed seismic analysis of bund wall slope stability using pseudostatic and pseudodynamic methods [15]. In their work, Nimbalkar and Choudhury used a horizontal section method to assess the seismic stability of the bund wall, taking into account the forces of seismic inertia acting on the dam collapse prism [16]. Chakraborty and Choudhury presented a static and seismic analysis of the stability of the bund wall [17]. Seismic stability analysis was carried out based on data from the 1989 Loma Prieta earthquake. The analysis of the results was carried out using the geotechnical software systems FLAC 3D and TALREN 4. Hamzeh Fallah and Hossain Noferesi used the following methods to assess the dam stability against a design earthquake: pseudostatic analysis, sliding block model, Singh empirical dependences, etc. [18].

According to regulatory documents, when calculating the stability of hydraulic structures of I and II classes of responsibility, it is recommended to use calculation methods for fixed shear planes, in which the forces acting on the shear surface are determined from the results of calculations of the stress-strain state, as well as methods of numerical modeling of the stress-strain state [SP 39.13330 2012 Rock fill dams]. When calculating the seismic resistance of hydraulic structures, depending on their type and class, methods of various theories of seismic resistance should be used [SP 358.1325800 2017 Hydraulic structures. Rules of design and construction in seismic-prone regions].

2. Experimental technique and theoretical approaches

Engineering and numerical calculation methods are used to assess stability after seismic impact. There is discusses only numerical methods for assessing the seismic stability of an embankment dams. The calculations were carried out in two-dimensional and three-dimensional problems in the PLAXIS
geotechnical software package. This program allows to carry out a dynamic calculation in two ways: a direct dynamic method and a pseudo-static method.

In the first method, the dynamic impact is modeled using prescribed displacement as a function of time or using a dynamic load. The applied dynamic impact is the multiplication of the input static displacement or static load value by the corresponding dynamic multiplier which can be represented by an accelerogram, velocigram, seismogram or a load-time diagram. Static components of displacement or load should be taken equal to one. Modeling the seismic impact is possible only using prescribed displacement which is applied to the bottom of the calculation model. Dynamic load is used to describe the dynamic impact created by moving vehicles, operating mechanisms and other mechanisms which create dynamic vibrations.

The second method is based on the application of accelerations in fractions of the gravity 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 acceleration is applied to the entire model so the pseudostatic method is only applied to simulate an earthquake and cannot be applied to simulate the dynamic effects of a moving vehicle or operating mechanisms.

In order to study the influence of each simulation method of seismic impact on the stability of an embankment dam and to consider the influence of soil properties, the time of application of the seismic impact, the number of accelerogram components, etc. on the stability of an embankment dam, several simulation cases were considered in a two-dimensional problem. The simulation model was a test problem. Soil properties were taken from a real site of an operating hydroelectric power station (HPP).

The next several simulation cases were considered:

1. Determination of the natural stability of an embankment dam without taking into account the application of seismic impact.
2. Modeling an earthquake by a direct dynamic method with various combinations of taking into account the direction of the axes to which accelerations are applied.
3. Modeling an earthquake by a direct dynamic method taking into account the self-induced vibrations of an embankment dam. They were modeled by creating an additional dynamic calculation stage without applying accelerograms.
4. Calculation of seismic impact by direct dynamic method with static and dynamic deformation properties and undrained strength of soils.
5. Determination of the influence of the full accelerogram of the seismic impact on the stability of an embankment dam and the initial section of the accelerogram with peak vibration amplitudes.
6. Modeling of seismic impact by a pseudostatic method with the application of averaged accelerations of accelerograms in fractions of g.

After each stage of the dynamic calculation the stability of the slopes of an embankment dam was calculated using the "φ-σ reduction" method. This method implies a gradual decrease of the strength properties of soils until a loss of stability of the slopes occurs. Further the safety factor is determined as the ratio of the initial strength properties to the strength properties obtained at the moment of destruction.

The calculation scheme of the test problem in a two-dimensional problem is shown in figure 1. The physical and mechanical properties of soils are presented in table 1.
Figure 1. Calculation scheme of the embankment dam in a two-dimensional problem.

Table 1. Physical and mechanical properties of soils.

|          | Relative density, $\gamma_{\text{unsat}}/\gamma_{\text{sat}}$ kN/m$^3$ | Modulus of deformation, $E$, MPa | Poisson ratio, $\nu$ | Cohesion, $C$, kPa | Internal friction angle, $\phi^o$ | Undrained strength, $s_u$, kPa | Filtration coefficient, $\kappa_c/\kappa_y$, m/day |
|----------|-------------------------------------------------|---------------------------------|----------------------|-------------------|---------------------------------|-------------------------------|-------------------------------------|
| Base     | 17.0/21.0                                       | 50                              | 0.30                 | 1                 | 35                             | -                             | 0.01                                |
| Prisms   | 16.0/20.0                                       | 20                              | 0.33                 | 5                 | 31                             | -                             | 1                                   |
| Core     | 16.0/18.0                                       | 1.5                             | 0.35                 | -                 | -                              | 5                             | 0.001                               |

To calculate the effect of seismic impact on the stability of an embankment dam in a three-dimensional problem the bund wall was modeled from a real object (class I of a hydraulic structure). The bund wall is earth-and-rockfill, faggot, homogeneous with a ground water cutoff on the upstream slope. The maximum height of the dam is 103 m, the maximum width at the base is 630 m. The construction of the bund wall is carried out in three stages. Figure 2 shows the calculation scheme of bund wall. Table 2 shows the calculated physical and mechanical properties of the dam body and the adjacent soil area.

Figure 2. Calculation scheme of bund wall in a three-dimensional problem.
Table 2. Calculated physical and mechanical properties of the dam body and soil area.

|               | Relative density, $\gamma_{\text{unsat}}/\gamma_{\text{sat}}$ | Modulus of deformation, $E$, MPa | Poisson ratio, $\nu$ | Cohesion, $C$, kPa | Internal friction angle, $\phi^\circ$ | Filtration coefficient, $\kappa$, m/day |
|---------------|------------------------------------------------------------|---------------------------------|---------------------|-------------------|--------------------------------------|----------------------------------------|
| **Dam body**  | 21.0/21.4                                                   | 50                              | 0.27                | 2                 | 38                                   | 3.0                                    |
| **Soil area** | 14.0/18.0                                                   | 10                              | 0.35                | 2                 | 25                                   | 0.01                                   |

3. Results
The calculation of the stability of an embankment dam in a two-dimensional problem showed that the safety factor of an embankment dam before the application of seismic impact is 1.744. Figure 3 shows a scheme of an embankment dam and a sliding prism formed over the most weakened surface.

![Diagram of embankment dam]

**Figure 3.** Stability of the embankment dam before the application of seismic impact.

During the calculation of the stability of the dam after the application of seismic impact the safety factor turned out to be 0.979 (figure 4). Seismic impact was simulated by the direct dynamic method with the application of accelerograms along the X-axis and Y-axis. Thus, there is a loss of stability of an embankment dam after seismic impact. The calculation was carried out during the action of the peak vibration amplitudes located at the initial section of the accelerogram. This case is the worst in terms of a loss of stability.
Figure 4. Stability of the embankment dam after the application of seismic impact by the direct dynamic method, taking into account the application of accelerograms in all directions of the axes.

The dynamic impact is the multiplication of the static component of the displacement or load and the dynamic multiplier. So in the next simulation case the difference of the influence on stability was shown without taking into account the static component. The safety factor turned out to be equal to 1.742. It practically does not differ from the safety factor which obtained before the application of seismic impact. Therefore, it is important to consider the static components of the displacement.

Loss of stability does not occur instantly and it is a process which takes place in time. Therefore, it is important to understand what moment of seismic impact the determination of stability is the most correct. The stability of an embankment dam at the moment of the action of the peak amplitudes of vibrations is 0.979, at the moment of the end of the seismic impact and the complete damping of vibrations - 1.532. In the first case, the seismic impact lasted 15 seconds. In the second case, it lasted 40 seconds. The calculation results showed a large difference in the safety factors. It can be concluded that the determination stability at the peak of the strongest vibrations can lead to obtaining an unreliable safety factor because the duration of this acceleration is short and may not be sufficient for the loss of general stability.

Determination of the stability of an embankment dam after the end of seismic impact with free vibrations of the dam showed that the safety factor is 1.634. Consequently, sometime after the earthquake the stability will become higher, but it will still be less than the stability before the seismic impact.

Direct dynamic calculation with static and dynamic deformation properties of soils showed that in the first case the safety factor is equal to 2.297 and in the second case it is 2.267. Thus, the deformation properties of soils practically do not affect the stability of an embankment dam. However in this software package it is possible to set the damping properties of soils. But due to the fact that
they were not determined during engineering and geological surveys it is not possible to assess their impact on stability. This question can be interesting and useful for further research.

During the dynamic impact excess pore pressure arises in the soils. Therefore, the case of setting the seismic impact by the direct dynamics method with undrained strength of soils was considered. He showed that the stability will be equal to 1.335. Consequently, undrained soil behavior can affect the stability of an embankment dams.

The calculation of the seismic impact by the pseudostatic method showed that the stability of the an embankment dam will be equal to 2.308. This value is overestimated because it is a known fact that any dynamic influence has a negative impact on stability to varying degrees [SP 358.1325800 2017 Hydraulic structures. Rules of design and construction in seismic-prone regions]. Therefore, the stability after an earthquake cannot exceed the natural one.

Table 3 shows the results of calculating the safety factor for all simulation cases in a two-dimensional problem.

| Simulation case                                           | Safety factor |
|-----------------------------------------------------------|---------------|
| The natural stability                                     | 1.744         |
| Calculation without static components                      | 1.742         |
| Calculation with static components                         | 0.979         |
| Impact of free vibrations                                  | 1.634         |
| Calculation with full accelerogram                         | 1.532         |
| Calculation with static deformation properties of soils    | 2.297         |
| Calculation with dynamic deformation properties of soils    | 2.267         |
| Calculation with undrained strength of soils               | 1.335         |
| Pseudostatic method                                        | 2.308         |

During the calculation of the bund wall in a three-dimensional problem the seismic load was modeled in two ways:

1. Modeling of seismic impact by a pseudostatic method with the application of averaged accelerations of accelerograms in fractions of g.
2. Modeling by a direct dynamic method with the application of accelerograms along three axes. The full duration of accelerograms is 55 seconds. The maximum values of the vibration amplitudes occur in the first 15 seconds. Therefore, the duration of accelerograms was reduced to 15 seconds. After the application of the seismic load phase a free vibration phase of 5 seconds duration was simulated. The calculation for the full accelerogram is impractical because the calculation time increases several times.

The next results were obtained in a three-dimensional problem:
- the safety factor of the bund wall before the application of seismic impact - 2.204;
- after application of seismic impact by pseudostatic method - 1.948;
- after application of seismic impact by direct dynamic method – 1.466.

4. Discussion
The next main conclusions which based on the research performed can be made:
1. The stability of an embankment dam before seismic impact is equal to 1.742.
2. During direct dynamic analysis it is necessary to take into account all static components of displacements and loads because the dynamic impact is the multiplication of the static component of the displacement or load and the dynamic multiplier. The stability of an embankment dam with all the static components of displacement is 0.979 while without taking them into account it is 1.742. Consequently, in this case the seismic impact is not taken into account.
3. Calculation of stability at the moment of the peak vibration amplitudes of the earthquake showed that the safety factor of an embankment dam is 0.979, at the moment of vibration damping - 1.532, after the earthquake - 1.634. Therefore, determining the moment of time when the stability of an embankment dam will be assessed is a fundamentally important moment. Determination of stability during the impact of peak vibrations is not correct because the safety factor can be greatly underestimated due to the insufficient time of the peak load for the loss of general stability.

4. The calculation results showed that deformation properties of soils practically do not affect the stability of an embankment dam. It should be noted that in PLAXIS software package it is possible to set the damping properties of soils and consider their influence on the stability of an embankment dam. Such calculations were not performed in this research but it is an interesting topic for further research.

5. During the seismic impact excess pressure occurs in the pores of the soil. Soils acquire undrained behavior. Then the strength of soils will be characterized by undrained strength. The calculation results showed that in this case the stability of an embankment dam will be equal to 1.335. That is, taking into account the development of the process of occurrence of excess pore pressure will most likely lead to an additional decrease the safety factor.

6. The calculation of the seismic impact by the pseudostatic method showed that the stability of an embankment dam will be higher than its stability before the application of the seismic impact. The obtained value of the safety factor is not correct because an earthquake has a negative impact on stability to varying degrees.

7. The calculation of the bund wall in a three-dimensional problem showed that the calculation by the pseudo-static method gives an overestimated safety factor, in contrast to the direct dynamic method of setting the seismic load.

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