Earthquakes and seismic safety of waterworks facilities in the Central Asian region

M Akhmedov²*, D Juraev¹ and I Khazratkulov¹

¹Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan
²Institute of Mechanics and Seismic Stability of Structures Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

rustamru@yahoo.com

Abstract. Central Asian region is an earthquake prone zone. At water management engineering, one of the central and great role play dams, water supply systems, etc. The seismic safety of these objects has great importance. In areas subject to seismic effect, the cases were observed when such structures were significantly damaged, and in some cases even destroyed. It leads to the long-term shutdown of the main water supply systems and it causing great material losses. The main aim of the issue is an analysis of the effects of strong earthquakes for waterworks facilities, proposing measures that are necessary for the urgent determination of the technical condition of an operating structure and the development of recommendations for further safe operation. There were considered lessons from past events also and strategies for sustainable development in the future by taking into account local features.

1. Introduction

In most agricultural countries, irrigation facilities, many energy, and lifeline structures are associated with the construction of various dams, dams, and barriers. They are the most important objects of the economy of these countries, and especially countries where water resources are limited and rivers have variable flows, sometimes with very low water levels.

Therefore, to meet the needs of the economy in these countries, the corresponding accumulation of water is necessary. And in this regard, reservoirs play an important role for generating electricity, for evenly satisfying the needs of agriculture (for example, at present, reservoirs in the Republic of Uzbekistan supply about 90% of agricultural production with water, hydroelectric power plants provide 40% of electricity), supplying drinking water to the population and the whole for the stable functioning of other sectors of the economy, most importantly.

Earthquakes pose the greatest threat to dams and other hydro-technical structures. Statistics show [1-4] that the damage caused to retaining structures by seismic factors totals dozens of cases, and taking into account the earth dams - hundreds of cases, including high dams erected from various types of structure. Their failure is fraught with serious economic losses since even their partial destruction can have catastrophic consequences: economic damage, numerous losses in human lives, ecology violation, emergency rescue operations and elimination of the consequences, and many other aspects.

It was established to ensure the safe operation of hydro-technic structures it is necessary to analyze dam damages (or other weak positions) both in pre and post-disaster periods, as well as to classify and
generalize their damages by type of structure and dam size. For further safe operation of hydro-
technical structures, the need for an urgent assessment (quick inspection) of the technical condition of
it after an earthquake. It is necessary to periodic monitoring and inspection of hydro-technical
structures and the organization of regular repair and restoration works. These positions are accepted as
initial demands everywhere.

2. Methods
Based on the experience of studying the consequences of several earthquakes occurred in the past in
our republic (Tashkent, 1966, Gazly, 1976, 1984, Nazarbek, 1980, etc.), a methodology and concepts
for assessing seismic risk for Tashkent area were developed with the aim to plan the measures to
reduce it [1]. These methods and concepts are acceptable for dams and other hydro-technical
structures, with certain provisions that take into account their specifics.

3. Results
3.1. Main part
Only in the last 40-50 years, dozens of large dams all over the world have suffered serious damage due
to the earthquakes. A good example of this is the consequences of the Sichuan earthquake in China in
2008, May 12, with magnitude $M = 8$ on the Richter scale and intensity $J_0 = 11$ points on the MSK-64
scale. 69 197 people died, about 18 thousand people were missing, 288 431 were injured. The
earthquake occurred in the seismically active Longmenshan fault, which runs along the western edge
of the Sichuan basin, separating it from the Sino-Tibetan mountains. Figure 1 shows the types of
damage in “Zipingpu” dam in Sichuan and others [2 – 6].

![Figure 1. View of “Zipingpu” dam after the earthquake [2, 3, 5, 6]](image)

As a result of the ground motion of varying intensity, 1583 dams of various types were damaged,
including several large ones. The stone-fill Zippingu dam (156 m) designed for 8 points, with a
reinforced concrete screen was located as far as 17 km from the epicenter. Under the influence of the
earthquake, the dam settled down to 70 cm and shifted to the downstream to 18 cm; damage to the
screen and parapet on the crest was observed. Hydroelectric power station facilities with a hydraulic
unit capacity of 700 MW suffered some damage. (Figure 1) A 102-meter-high stone-fill Biku dam
with a loamy core, designed for 7.5 points earthquake suffered an earthquake with a maximum settlement of 24 cm and 30 cm displacement. Hydroelectric power station facilities of the Sheypay arch-concrete dam of 132 m high, designed for 7 points earthquake were damaged (Figure 2) [3]. Also, due to the landslides occurrence, dangerous secondary consequences appeared – the dykes, their breakthrough, and flooding of the terrain below. None of the large dams collapsed, although they were only 12-17 km from the epicentre of the earthquake. Their safety was ensured by high quality design, proper operation, and timely adoption of necessary measures in emergencies.

Figure 2. Sheypay dam [2, 3]

At the Bhuj (India) earthquake on January 26, 2001 with $M = 7.9$, damage of varying degrees was caused to 245 small earth dams and dykes (Figure 3) [2]. During this earthquake, with intensity $J_0 = 8$ points, 80 thousand people died [3].

Two of the three dams in the area of El Cobre (Chile) collapsed as a result of an earthquake of 8–9 points in 1965. The catastrophe turned El Cobra into piles of ruins. Landslides and floods completed the destruction. Water broke through the Soldado Dam and washed away all the downstream villages. About 500 people died in the El Cobre region. [7]

Currently, according to the International Center for Dam Safety Analysis, there are more than 800 thousand dams of various types in the world, of which 50 thousand are higher than 15 m. The accumulated information includes more than a thousand cases of destruction of earth dams of similar sizes [8].

Widely known are the following major national accidents in dams with human casualties, great social and environmental damage: Machu-11 (India); Buffalo Creek, Canyon Lake and Titon (USA); Tous (Spain); Touhou (China); Oros (Brazil), Haiokori (South Korea) and others [9].

Over the past 100 years, about 400 earth dams, levees, and embankments have been affected by earthquakes of various intensities from 4-6 points and higher [9]. At the same time, the number of damages and accidents in these structures caused by earthquakes in different countries was from 1 to 6% compared with the number of accidents from other causes. According to the static data of 1966, for example, from 1226 dams in Japan, (90% of which higher than 15 m), that suffered deformations and damage, only 6% of cases were associated with earthquakes.

The Chiryurt Dam on the Sulak River (Russia) built from gravel-pebble soil with a central loamy core during a strong Dagestan earthquake on 05/14/1970 received quite significant deformations and damage. Calculation and design of the dam located in the area of 7 points seismicity were carried out according to Building Code - SNiP II-A/12-62 based on the static theory of seismic resistance. The
safety factors for shear stability along circularly cylindrical sliding surfaces were obtained equal to 1.50 – for the upstream and 1.25 – for the downstream slopes at the base; 1.19 for the upstream and 1.25 for the downstream slopes under special combinations of loads (including seismic ones). Large cracks formed as a result of the earthquake on the dam crest along the entire length of the structure (figure 1), along the crest axis, and at the edge of the upper and lower slopes. Damage to parapets and linings were observed. In general, the dam withstood the effects of a severe earthquake - it did not collapse. Under repair, the top layer of loosened soil 2.6 m thick was removed and replaced with another. The linings and parapets were reconstructed (figure 4) [14].

Analysis and assessment of damage to earth dams showed that their seismic resistance is greatly influenced by the quality of the construction process:

- under the same earthquake, the Bowket dam, erected with compaction, was not damaged [14], while the Dry Canyon dam, erected without compaction, was damaged, although it was located further from the epicenter [Earthquake with \( M = 7.7 \); 21.06 1952 in Arvin-Thcheli, USA];

- the choice of design of anti-filtration core elements and the screen made of plastic loams, soil mixtures turned out to be more earthquake-resistant than the rigid concrete cores, screens or diaphragms;
the quality of water-resistant elements coupling with lateral prisms and sides of the canyon should be high due to the possibility of soil stratification and cracking in the juncture zone of heterogeneous materials (for example, between the core and the outer prism in the Ono dam; the concrete core and the outer prisms in the Hebgen dam [Earthquake with $M = 7.1$; 08/17/1959, Lake Hebgen, Montana, USA].

- the choice of the slope fastening construction (for example, the concrete coverings of the lower slopes of Piedmont, Lower Muroyama and Sheffield dams on the filtering layer suffered significant damage and settlement, while their upstream slopes with stone loading were not damaged) [14,20-23];

- the laying of concrete pipes and culverts in soil has an adverse effect on the seismic resistance of earth waterworks, since the violation of their integrity even under weak earthquakes can lead to serious damage, and in some cases to the destruction of structures (Lower Govel dam, Tarbela) [14, 15].

But there are cases when stone-fill and concrete dams were destroyed by the earthquake. For example, a concrete gravity dam collapsed during the Chi-Chi earthquake (height 25m, magnitude $M = 7.6$, and a focal depth $h = 10$ km), in Taiwan in 1999 (Figure 5) [2, 3].

The effects of earthquakes of varying intensity over 100 dams and hydro-technical structures made of concrete are observed and wide investigated. Only 15 cases of damage and destruction are known, and more than half of them received damage in the form of cracks. Damage to concrete dams was observed only from earthquakes with an intensity of 7 points or more. Several culverts, small masonry dams located on soft soils, were destroyed by strong earthquakes.

In general, low structures up to 20 meters high, as well as buttress dams, are most damaging. Three out of eight buttress dams - were damaged. The most earthquake-proof were concrete gravity and arched dams, which experienced strong earthquakes with an intensity of 8-9 points, but did not receive significant damage.

The largest and most famous dams that have experienced seismic effects, and some of which are the cause of the earthquake, are presented in Table 1.

Today it is already well known that seismic resistance is increasing due to the filling of large reservoirs in various regions of the world. An increase in local seismicity is also recorded when pumping fluid into deep wells and faults. High intensity of some earthquakes initiated by such factors sometimes leads to significant destruction, dam damage, and human casualties [2 – 6].

![Figure 5. Destruction of the Shi-Kan dam in Taiwan during the Chi-Chi earthquake 09/09/1999 [2, 3]](image)

| Name of the dam | Country | Height, | Reservoir capacity |
|-----------------|---------|---------|--------------------|

Table 1. Dams subjected to strong seismic effect
The analysis of numerous earthquakes initiated by hydro-technical structures allows making the following generalizations. Most often, the ground motion shocks have a magnitude of less than 2.0-2.5, sometimes they reach 3.5-5 and only rarely they are > 6, the focus depth is mainly <5-6 km.

Only in some cases, the earthquakes had devastating effects: the Kremasta region in Greece, Koyna in India Cariba on the Zambezi River, Wyont in Italy.

Not all induced earthquakes are dangerous. They are dangerous when the maximum head reaches 90-100 m, and the water volume exceeds 10km$^3$ [9, 14]. The probability of shocks increases with increasing water surface.

These examples once again confirm that the safety aspect is of particular importance: firstly, there is a need to ensure the safety of each dam, for this, it is necessary to take all measures to ensure that this facility does not pose a threat to people's lives, their health, property, and to the environment.

As can be seen, when excavating a parallel tunnel, the stresses around the mine increase, in this case, up to 20%. But it should be borne in mind that the existence of horizontal thrust and the possible anisotropy of rock mass were not taken into account. In general, as can be seen the stress concentration in tunnel corners is significantly high compared to other sections and here the likelihood of a crack and its initiation (propagation) is maximal.

Secondly, dam safety is directly related to the sustainability of construction projects, to social and economic factors. With this in mind, the safety problems of such facilities should be given attention to at all stages of their life cycle.

### 3.2. The state-of-the-art of the issue in Uzbekistan

Now, out of 55 operating dams, there are:
- homogeneous earth ones – 29 dams;
- stone-earth ones with a core – 17 dams;
- earth ones with a screen – 6 dams.

In Central Asia, the Charvak (Uzbekistan), Nurek, Rongun (Tajikistan), and other dams were built from gravel-pebble and stone-earth materials.

The reservoirs of the Republic are divided into two types – mountain ones and plain ones. Mountain reservoirs include, for example, the Charvak dam; the plain ones are the Tuyamuyun, Uchkizil, Kukmazare, Chardarya, Talimarzhan, Katta-Kurgan and others.

The main feature that distinguishes the mountain reservoirs from plain ones is the large filling depth, up to 300 m, with small areas of water mirror and significant drawdown values, up to 30-60 m.

Valley reservoirs are characterized by shallow depths (40 m), and relatively large areas of water mirrors, their banks are represented by ledges of river routes.

The main danger, which can cause large landslide displacements, is the overflow of water through the dam, the overlap of the entrance portal, and the capture of large areas. In addition to landslide processes, settlement processes are intensively developing.
Earthflows and mudflow occur after an abrupt decrease in the reservoir, they vary from 10 to 1500 m³, with the prevailing earthflow of a volume of up to 100 m³, having a diking and elongated form along the coast.

Of particular danger are landslides of the diking that contribute to the lake formation. Now in the mountain folded regions of Uzbekistan and adjacent territories of Kyrgyzstan and Tajikistan, there are about 43 mountain dammed lakes. Of these, 11 are in Uzbekistan, 119 in Kyrgyzstan, 12 in Tajikistan. Four lakes located in the Pskem river basin (Uzbekistan) are dangerous due to possible breakthroughs. In general, the volume of the dammed lakes of the Republic is 17.09 million m³, in adjacent regions of Kyrgyzstan - 109.37 million m³, Tajikistan - 416.97 million m³. One of the typical examples of unloading is a breakthrough of a dammed lake Yashinkul, located on the northern slope of the Alai ridge at an altitude of 2600 m, in the valley of the Tegirmoch river in the Isfayramsai river basin. The settlement of the dam crest of the lake Yashinkul, then its destruction in the central part and the formation of a breakthrough wave occurred as a result of the Tashkent earthquake on April 26, 1966 [4].

By the time of the breakthrough, 6.6 million m³ of water was accumulated in the lake. The beginning of the breakthrough was marked by the fall out of individual blocks from the body of the blockage and subsequent erosion. During the breakthrough, two powerful waves 15 and 10 m high arose. Within 2-3 hours all the water accumulated there was completely drained from the lake, which in the form of mudflow passed through the Isfayramsai river valley with maximum flow rate up to 2200 m³/s. The average mudflow rate was 4.5 – 5.8 m/s, the height of the head wave in some areas reached 10-15 m. This breakthrough was not an isolated fact, similar breakthroughs occurred in the past in other regions of Central Asia.

Field observations of the behavior of earth dams show that in certain sections of the upstream and downstream slopes, as well as in crest zones, the greatest stress states arise, which can negatively affect the structure strength, and can lead to damage or destruction during earthquakes.

Many water facilities in the Republic have already worked out or are close to working out a 50-year service life and are waiting for their overhaul and replacement of obsolete equipment, strengthening of the downstream basins, etc. There is practically no monitoring of the mudflow storage facilities, therefore it is difficult to judge their technical condition.

For the territories with an additional risk factor such as a high level of seismic activity, the issue of preventing the tragic and devastating consequences of strong earthquakes in hydro-technical structures and, in particular, dams, is especially important and requires a special individual approach. All Central Asian states are located in a seismically active region where catastrophic earthquakes occurred and the probability of their occurrence in the future is very high. Therefore, the possible destruction of dams and large water reservoirs of man-made and natural origin, under the influence of earthquakes pose a danger to the Central Asian region. For example, while the danger of flooding the cities of Uzbekistan comes from the Charvak reservoir, the collapse of the dam on Lake Sarez (Tajikistan) [18] threatens several cities in Uzbekistan, Tajikistan, Afghanistan and (to a lesser extent) Turkmenistan [8, 19].

Indeed, earthquakes pose the greatest danger to dams and reservoirs. The underestimation of seismic activity factors in the region may lead to damage or destruction of hydro-technical structures with extremely serious consequences. Statistics show that dam accidents due to the seismic factor number dozens of cases, and taking into account earth dams, hundreds of cases [9, 11].

As a result of these destructions, the so-called “breakthrough waves” are formed. These waves initiated as a result of the breakthrough of dams or blocked lakes, in mountainous terrain conditions, have a completely different nature in comparison with similar ones occurring on flat rivers. The main difference between these waves, called similarly, is that on plain rivers the maximum parameters of the breakthrough wave are observed at the point of dam destruction or blockage, while in mountain rivers, depending on the terrain slopes, it can be shifted several tens of kilometers down the flow. Therefore, under mountain conditions, there is an effect of an increase in specific energy of the flow cross-section as it moves; this effect is not observed on the plains.
All this indicates the need for urgent consideration of the issue of seismic vulnerability of hydro-technical structures and the safety of their operation. This could be achieved, in our opinion, by periodic control inspection of structures, organization of regular repair and restoration work, as is done in civil and industrial construction projects. The foregoing applies to all water facilities located in seismically active regions, especially if they include hydro-technical structures that have been in operation for more than 50–60 years and need an overhaul and reinforcement following the requirements of seismic construction standards [1, 2, 3].

Conducting periodic assessments of technical condition of hydraulic structures and related measures to eliminate dam damage makes it possible to prevent potential destruction of water bodies. For this, it is necessary, first of all, to analyze and process dam damage both in peacetime (operating dams) and after the impact of strong earthquakes; to classify and summarize damage by types of structure and dam size. To reduce the risk of destruction, including seismic risk, it is necessary to take appropriate reinforcement measures at the identified damaged points taking into account other categories of damage causes [2, 3, 10, 11, 12, 13, 14], and to carry out restoration work.

4. Conclusions

In countries, which are mostly agricultural, the irrigation facilities, energy, and utility infrastructure systems are associated with the construction of various dams, levees, and barriers. They are the most important objects of the country’s economy, and an increase in their stability, reliability, and safety of operation is the most important problem since even their partial destruction can have disastrous consequences - enormous economic loss, numerous casualties, and environmental damage.

With this in mind, to carry out the tasks related to determining the technical condition of dams and other hydro-technical structures, it is necessary to conduct a study to assess and reduce the seismic risk of dams and other important hydro-technical structures using modern methodologies based on international and domestic experience [18, 19, 20, 21, 22].

Necessary to develop the next structural and nonstructural measures:

- provide in situ seismic hazard analysis;
- to develop seismic safety assessment criteria for hydro-technical structures (include it in legislative norms);
- to organize continuous dam monitoring stations by nondestructive control method;
- selection and chose the seismic design criteria for concrete and earth dams separately;
- modeling of soil-structure interaction response;
- determination of dynamic material properties;
- to develop quick inspection methods for a dam in pre and post-disaster periods;
- to organize a restoration strategy.

An analysis of earthquakes’ impact on dams confirms once again that their safety has great importance.

In our opinion for increasing the stability of water work systems and their safe operating, it is necessary, periodic control inspection and periodic assessment of the strength and reliability of these structures. This position applies to all water management facilities of Uzbekistan and trans border countries because many of these objects have already worked out or are close to working out for 40-50 years, their safety reserves are exhausted and need major repairs and equipment replacement.

References

[1] Bradlow D D, Palmieri A and Salman M A 2003 Legal framework for dam safety (Comparative analytical review Washington D C: THE WORLD BANK report)
[2] Akhmedov M A 2004 On damages and seismic resistance of water work objects Reservoirs, emergencies and stability problems pp 15-31
[3] Akhmedov M A, Salyamova K 2018 Statistical analysis of damages and destructions of soil dams Int Sci and Practical Conf pp 104-113
[4] Akhmedov M A, Salyamova K 2016 Analysis and assessment of damage to hydro-technical
structures (Tashkent: FAN)

[5] Akhmedov M A, Salyamova K 2016 Analysis and assessment of damage to hydro-technical structures (Tashkent, FAN)

[6] Chan E Y 2008 The untold stories of the Sichuan earthquake The Lancet doi.org/10.1016/S0140-6736(08)61141-1

[7] Chigira M Wu X, Inokuchi T and Wang G 2010 Landslides induced by the 2008 Wenchuan earthquake (Sichuan, China Geomorphology)

[8] Dobry R, Alvarez L 1967 Seismic Failure of Chilean Tailing Dams J Soi Mech Found Div 93(6) pp 237-260

[9] Malik L K Emergencies related to hydro-technical engineering http://www.cawater-info.net/bk/dam-safety/files/malik1.pdf

[10] Rashidov T R, Kondratiev V A, Akhmedov M A and Tuchin A I 2009 Strategy of reduction of seismic risk for hydro-technical structures. Performance-Based Design in Earthquake Geotechnical Engineering-from Case History to Practice Proc of the international conference on performance based design in earthquake geotechnical engineering pp 975-984

[11] Abirov R A 2016 The seismic risk mitigation problems in urban areas of Central Asia Proceedings of the 6th International Disaster and Risk Conference: Integrative Risk Management - Towards Resilient Cities IDRC Davos p129-130

[12] Abirov R A, Akhmedov M A 2016 The impact of earthquakes on water works objects and its safety problems Proceedings of the 6th International Disaster and Risk Conference: Integrative Risk Management - Towards Resilient Cities IDRC Davos p.115

[13] Sagdullayeva D A, Maxmudova Sh A, Adilov F F, Abirov R A, Khazratkulov I O and Nasirov I A 2020 On stability of slopes in mountain zones. Case study J Phys Conf Ser 1425 doi.org/10.1088/1742-6596/1425/1/012016

[14] Yegian M K, Marciano E A and Ghahraman V G 1991 Seismic Risk Analysis for Earth Dams Journal of Geotechnical Engineering. doi.org/10.1061/(ASCE)0733-9410(1991)117:1(18)

[15] Gao L, Zhiqiang H 2005 Earthquake safety assessment of concrete arch and gravity dams Earthq Eng Eng Vib 4(2) pp. 251-264 doi.org/10.1007/s11803-005-0008-9

[16] Krasnikov N D 1981 Seismic resistance of hydro-technical structures from earth materials (Moscow, Energoizdat)

[17] Lorrai C, Pasche N 2007 Tarbela Dam-Case Study (Zurich, ETHZ)

[18] Gupta X, Rastogi B 1979 Dams and earthquakes (Moscow, MIR)

[19] Rysbekov Yu Kh 1999 Lake Sarez - as a potential threat to national and regional security Proc first republic.scientific and practical conf pp 29-31

[20] Savinov O A, Sumchenko E I 1976 Seismic effects on hydro-technical structures Issue 1 Damage to the dams during earthquakes

[21] Mirsaidov M M Sultanov T Z 2014 Assessment of stress-strain state of earth dams with allowance for non-linear strain of material and large Magazine of Civil Engineering 49(5) pp. 73-82 136-137 doi.org/10.5862/MCE.49.8

[22] Mirsaidov M M, Toshmatov E S 2019 Spatial stress state and dynamic characteristics of earth dams Magazine of Civil Engineering 89(5) pp. 3-15 doi.org/10.18720/MCE.89.1

[23] Mirsaidov M M, Sultanov T Z and Sadullaev A 2013 Determination of the stress-strain state of earth dams with account of elastic-plastic and moist properties of soil and large strains Magazine of Civil Engineering 40(5) pp. 59-68 doi.org/10.5862/MCE.40.7