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IMPACT OF CLIMATE CHANGE AND TIME-DEPENDENT HAZARDS ON DAM SAFETY

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ABSTRACT

This paper is concerned with the impact of climate change and other hazards on the safety of large dams. It is typical for most hazards from the natural environment, man-made environment and site-specific and project-specific hazards that they depend on time. Similarly, the safety criteria are also changing with time. Therefore, dam engineers have always been concerned with such changes and climate change is no exception. Because of these changes, which cannot be predicted at the time a dam is being built, safety evaluations have to be carried out periodically. Well-designed, well-constructed and well-maintained storage dams that satisfy current safety criteria have a long lifespan and therefore safety assessments must be carried out repeatedly. The reservoir may have a similar lifespan as the dam, but the use of the stored water will change with time and the useable reservoir volume may decrease due to sedimentation, whereas the basic function of the dam remains unchanged. The main hazards due to climate change that are addressed in this paper are floods, floating debris, mass movements and debris flows into the reservoir, which may endanger the safety of a dam. To account for all these time-dependent changes a resilient dam should be the solution, i.e., the dam should have certain reserves beyond the safety flood or safety evaluation earthquake. Mass movements are among the main climate change hazards for dams, but strong earthquakes can trigger many more landslides and rockfalls than the worst meteorological events. This means that certain hazards are more critical than climate change. Due to changes in safety standards in design codes, the design loads have been increased continuously for weather-affected loads and actions when climate change was not an issue.

1. INTRODUCTION

Large dam projects may be subjected to a large number of different types of hazard including hazards from the natural environment, man-made hazards, and site-specific and project-specific hazards. Most of them are time-dependent. The intensity of the hazards considered in the design and safety evaluation of large dams, may change with time. Therefore, as this paper is mainly concerned with the effects of climate change on dam safety, where the flood safety is the main safety concern, the chief reasons for time-dependent changes of the flood design and safety criteria are given. For the other hazards listed below the reasons for changes due to climate may be similar to the flood hazard, except for new hazards, which are mainly man-made and are unknown at this time:

(1) New information on flood hazard is available (e.g. new hydrological and meteorological data, increase in extreme rainfall, etc.);

(2) A major flood has occurred;

(3) New flood design and/or safety criteria are introduced;

(4) New methods for the evaluation of design and/or safety floods are introduced;

(5) The flood vulnerability of a dam has increased due to modifications, ageing etc.;

(6) The flood risk classification of dams has changed due to new flood safety guidelines;

(7) The flood risk has increased, e.g., due to the increase in the number of people living downstream of a dam, economic developments, changes in land use, deforestation in the catchment region, etc.

(8) The reservoir may be silted up requiring changes in the reservoir rule curves for usual and unusual operations or modifications in flood routing analyses, etc.

(9) New requirements due to emergency planning, e.g. new inundation maps for different flood and dam breach scenarios, etc.

Climate change will have a direct effect on (1) and a lesser effect on the other items, as, historically there is a trend to increase the safety standards for all types of natural hazards. Lowering of the safety standards would really be an exception. This development is illustrated in Fig. 1 in which the design criteria for snow loads in Switzerland are shown from 1892 to 1989, i.e. a period in time when climate change was not an important issue. The increase in snow loads is simply a consequence of new information on snow cover, the behaviour of buildings under snow load and increased safety standards. Actually, the snow loads have not been increasing during this period, but new types of structures were built, which were more vulnerable to snow loads than the old traditional buildings. These design and safety criteria for snow loads are typical for other actions from the natural environment. Safety standards are generally increasing, irrespective of climate change, but climate change may accelerate the process of changing design and safety criteria.

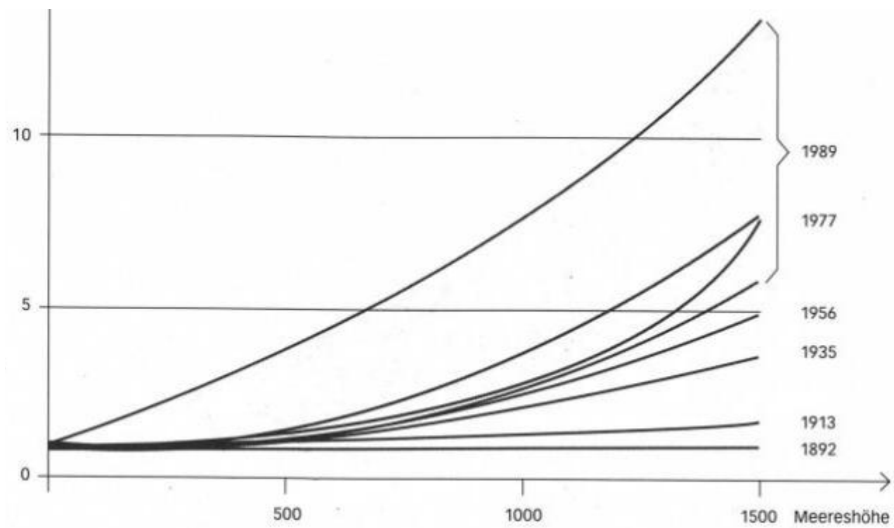

Fig. 1 : Changes in snow loads in Switzerland from 1892 to 1989 as a function of the elevation above sea level (snow load in kN/m^2)

A typical case of rapid change in the design and safety criteria within recent decades is the seismic hazard, which has undergone substantial changes within the last 40 years worldwide for all types of structures, including large dams. These changes had a larger impact on the seismic design and safety assessment of existing dams than any anticipated climate change effects. The changes in design of structures can best be seen in the frequent revisions of the widely used building code ACI 318-19 (Building Code Requirements for Structural Concrete, latest edition 2019) and the International Building Code (IBC-2021, latest edition 2021), which are partially updated every 3-6 years and 3 years, respectively. With such a frequent code update, new developments can be considered. Obviously, such codes are not updated as frequently in other countries. From this short discussion it can be concluded that in the design of structures, along with the progressing technological development, codes have always changed and therefore, the effects of climate change can be considered in such codes in the same way as technological progress. The basic difference between technological progress and climate change is that the long-term technological progress cannot be predicted such that it could be included in today‘s codes, whereas there are models to estimate the climate change for different scenarios. Irrespective of future developments, by periodically updating the codes, any time-dependent changes like climate change can be implemented taken into account using well-established procedures. These statements apply for new buildings and other structures including dams. However, in the case of large dams, it should become standard practice to carry out a detailed safety review periodically. This can be done with intervals of five years, as, for example, in Switzerland. By such a review all changes in the main hazards including climate change can be accounted for. The long-term effects of technological progress and changes in hazards, which are hard to quantify, do not really have to be considered in the specification of the design criteria. In view of major uncertainties the best way is to design resilient structures, i.e. structures that will not fail when the design loads and actions are exceeded.

If the safety evaluation shows any deficiencies, then the actions listed in Section 2.4 may be taken. This is already current practice.

2. MAIN HAZARDS FOR LARGE DAM PROJECTS

2.1 Hazards from the natural environment

The main natural hazards that are influenced by climate change are as follows:

(i) Meteorological or climate change hazards: These are multi-hazards, which for large storage dams include the following:

- Heavy rainfall causing floods and mudflows, rockfalls and mass movements at the dam site and reservoir rim, surface erosion or blocking access roads to dams, etc.
- Floating debris blocking power intakes and intakes of gated spillways.
- Strong winds causing water waves in the reservoir and reservoir bank erosion.
- Sediment transport (mudflows and debris flows) into reservoir and turbidity currents blocking low-level intakes during floods.
- Low and high temperatures, thawing and freezing, snow and ice avalanches, rockfalls, etc.
- Glacial lake outburst due to snow and ice melt or failure of ice dams in rivers, etc.

(ii) Seismic hazards: Seismic hazards are multi-hazards, which, for large dam projects, include ground shaking, movements on active faults or discontinuities in the footprint of a dam or reservoir, mass movements at the dam site and in the reservoir causing impulse waves, mass movements in the catchment area, etc. However, the seismic hazard, which is the result of tectonic processes, has nothing to do with climate change. The same applies to reservoir-triggered seismicity.

(iii)Landslide and rockfall hazards: Mass movements include the following:

- Mass movements can be triggered by heavy rainfall, earthquakes, changes in ground water table (e.g., seepage through abutments when reservoir level is increased or reservoir impounding) or by thawing of permafrost, etc.
- Mass movements (rockfalls, landslides) at the dam site and in the reservoir may cause impulse waves, block intakes of spillways and/or low-level outlets, and damage the dam body, equipment installed on the dam crest, spillway gates and spillway bridges, equipment, appurtenant structures, etc.
- Avalanches and ice falls, causing impulse waves in the reservoir and damaging appurtenant structures. Ice rock avalanches may originate in the catchment area as, for example, the hill slope failure in Uttarakhand in India on February 7, 2021.
- Debris flows due to high intensity rainfall, thawing, etc.

2.2 Site-specific and project-specific hazards

Site-specific and site-specific hazards, which may also be related to climate change, are as follows:

- Blockage of spillway gates (due to floating debris, ice jamming, etc.) causing overtopping of the dam.
- Erosion or cavitation damage due to extended operation of the spillway and/or low level outlets.
- Ageing (corrosion, biological growth, etc. due to higher temperatures and humidity), alkali-aggregate or sulphate reactions, inadequate frost resistance of concrete, and other ageing processes affected by temperature and humidity.
- Dam and safety-relevant elements do not satisfy current safety criteria (inadequate spillway capacity, etc.) and others.

2.3 Man-made hazards

Man-made hazards such as errors in the design and poor construction may be the most common hazards in any infrastructure project. They can be dealt with by proper quality assurance. The man-made hazards are not specifically related to climate change. The main problem is that delays in strengthening and rehabilitation works of flood control devices may increase the flood risk due to climate change. Timing plays an important role. The number of man-made hazards is very large; some of the most common ones with large consequences are listed below:

- Design errors.
- Ignoring or underestimating hazards.

- Changes in land use in the catchment, increasing the flood hazard, etc.
- Poor construction and/or substandard construction materials.
- Lack of maintenance and deficient dam safety monitoring.
- Faulty operation of equipment, inadequate rule curves for reservoir operation, etc.
- Deficient dam safety management procedures, lack of regular safety inspections and period safety assessment of the dam, delays in the rehabilitation of deficient dams.
- Deficient dam repairs or rehabilitation works.
- Sabotage, terrorism, acts of war, cyber criminality.
- Other hazards or unknown hazards.

2.4 Possible measures to be taken in the case of anticipated safety problems

In the design and safety assessment of large dams all possible hazards should be reviewed and addressed. If hazards are evolving or have occurred then the following measures can be taken to increase the safety of the dam and/or to reduce the consequences of a dam failure:

(i) Rehabilitation,

(ii) Partial draw-down of reservoir,

(iii) Full draw-down of reservoir,

(iv) Evacuation of the population in the downstream flood area, and

(v) Post-event evacuation and rescue of the population.

The most difficult hazards for large dams and infrastructure projects are those that cannot be predicted or where the warning times are very short. These hazards are earthquakes, sabotage, terrorism, acts of war, and as a new phenomenon cyber criminality, which cannot be predicted, therefore, if such events occur, only post-event evacuation and rescue are possible. The other hazards are less difficult to handle since more time is available for preventive actions. This is the case for the extreme events due to climatic change, which can be considered as a meteorological hazard. As climatic changes are slow processes compared to seismic events or terrorism, there should be adequate time for rehabilitation or adaption.

Moreover, the above list of hazards shows that, for example, the call for the urgent study of the safety implications of climatic change on dams without looking into all the other hazards, many of them being more critical than climatic change, shows a lack of understanding of current dam safety concepts.

3. DISCUSSION OF EFFECTS OF CLIMATE CHANGE ON DAM SAFETY

Dams are designed for extreme flood events and earthquakes, etc. For flood safety, the safety flood of large concrete and embankment dams is either taken as a 10,000-year flood or the probable maximum flood (PMF), respectively. In the case of earthquake safety the safety evaluation earthquake is either an extreme event with a recurrence period of 10,000 years or the maximum credible earthquake (MCE). Designing for the PMF and MCE means that no natural event is possible, which is larger than these extreme events, i.e. the dam is safe against any such events. There is obviously some ambiguity in this concept, as there are major uncertainties in the estimate of the PMF and/or the MCE. These uncertainties are due to the still limited knowledge regarding these events, the methods for estimating the design parameters from these events and the effect of climate change, etc., on the PMF, i.e. all these factors are time-dependent. Therefore, it is necessary to review the PMF and MCE periodically. It would be dangerous to think that PMF and MCE are invariants. As it would imply that the assumptions made for the PMF or MCE at the time of construction of a dam would still apply over its whole economical life, which could be much more than 100 years. It seems that the scientists doing research on climate change are not familiar with the safety concepts used by engineers. This can be concluded from all the warnings about climate change on dam safety, which appear frequently in the press. For, example, more frequent floods is not a problem as long as the floods are less than the safety flood. However, more frequent use of the spillway may increase erosion or cavitation damage, but a well-designed, constructed and maintained spillway should not be vulnerable to the increased number of days it is used.

If the PMF is not reviewed or updated periodically, dam failures are inevitable. An example of underestimating the safety flood is the flood of July 14, 2021, which overtopped the Steinbach dam in Germany by about 40 cm and eroded the downstream face as shown in Fig. 3. The maximum overtopping flow was 120 m3/s and the design flood 20.5 m3/s. If the dam safety had been reviewed periodically, examining worst-case scenarios, such events should not have happened. The claim of climate change should not be used as an excuse for such incidents.

Fig. 2 : Overtopping of Steinbach dam in Germany (14.7.2021). The paved road across the crest saved the dam.

The main dam safety concerns due to climate change are mass movements at the dam site along the reservoir banks. In addition, mass movements, the failure of landslide or ice dams or GLOFs in the catchment area may create large floods and debris flows in reservoirs. Dams forming small reservoirs or run-of-river power plants will be vulnerable to such events, which, e.g., are not uncommon in the Himalayas.

Extreme floods can be determined reasonably well for most rivers by statistical methods or other techniques. However, the triggering of mass movements is more difficult to deal with as during extreme events mass wastage may involve large areas. For example, during the May 12, 2008 Wenchuan earthquake in China with a moment magnitude of 7.9, more than 100,000 landslides and rockfalls were counted. A similar number was reported for the November 14, 2016 Kaikoura earthquake in New Zealand with a moment magnitude of 7.8. No similar events were reported for extreme rainfalls or storms. Therefore, the main events for triggering mass movements in mountainous regions are earthquakes. But earthquakes are local or regional events, whereas climate change is a global process, therefore regions may experience an increased number of landslides where seismicity is small or moderate. The identification of potential mass movements and their stability can be quite difficult, therefore monitoring slopes forming reservoirs and slopes in the catchment area is recommended. Moreover, as a protective measure an adequate freeboard must be provided as a protection against impulse waves. Such impulse waves are most critical if mass movements occur close to the dam or when the volume of the landslide is similar to the reservoir size. This is a problem for small dams and dams with small reservoirs as the mass of most landslides is small as shown in Fig. 3, where a mass movement was triggered by the impoundment of the reservoir.

Fig. 3: Minor rockslide due to impounding of the Rudbar Lorestan reservoir in Iran. This slide did not generate an impulse wave in the reservoir.

Overtopping of a small run-of river dam is more critical than the same overtopping of a high dam. For example, if a 10 m high concrete dam is overtopped by 2 m, the total water load is increased by 44%, whereas the same overtopping depth of a 100 m high concrete dam increases the total water load only by 4%. Therefore the sliding stability of the small dam may be a problem. In addition, in a small reservoir the impulse of the increased flow velocity in the reservoir must be considered in the sliding stability analysis of a dam.

We may conclude that dams with a small reservoir and run-of-river power plants should not be built in rivers where large debris floods or mass movements into the reservoir can occur, as they may silt up the whole reservoir and overtop dams and weirs. However, compared to seismic actions the hazard of mass movements and large inflows due to the failure of natural dams in the catchment area, caused by climate change and/or extreme weather events, is less serious than the same geological hazards caused by strong earthquakes. Therefore, earthquake safety helps to control these risks due to climate change as the corresponding earthquake risks are larger than those due to climate change.

As discussed in the previous section, there are many other hazards that may be affected by climate change, which, however, are less critical for the safety of the dam body than floods and mass movements. Floating debris created by high intensity rainfall may increase with time due to climate change. Floating debris may block spillways or low-level intakes, causing overtopping of dams. Today, floating debris are not only trees or bushes, but include all kinds of man-made objects and in particular large plastic sheets used, for example, in agriculture, which may block these safety-critical elements of a large dam project.

5. HOW TO DEAL WITH CLIMATE CHANGE EFFECTS ON DAM SAFETY?

As discussed in the Introduction, there are several reasons for the reassessment of the safety of dams, where climate change is just one of the many other reasons. Engineers have been familiar with such developments for many years, basically dating back to the creation of design codes and guidelines for different types of structures, including large dams. Therefore, hazards due to climate change can be dealt with in the same way as the many other hazards to be considered in the safety evaluation of large dams. Some of these hazards, especially those from the man-made environment, undergo changes, which are more dramatic than the slowly progressing climate change.

The solution to the time-dependent hazards affecting the technical safety of large dams is quite straightforward: Perform regular safety assessments of large dams based on latest information regarding the hazards, and the design and safety criteria. If the review shows that a dam does not comply with current safety criteria, then remedial measures have to be taken. In the short-term, restrictions in the use of the reservoir may be imposed. By lowering the reservoir, the safety of a dam is increased and in the case of failure, the resulting flood wave, will be reduced as the amount of water that could be released will be reduced. Remedial structural measures will have to be studied and implemented on a case-by-case basis.

This solution seems to be trivial, but this is the pragmatic and effective way in dealing also with climate change effects on the safety of large dams.

Moreover, dams and other structures have inherent safety reserves, which are essential for resilient structures. For that purpose, it is recommended to check also the safety of a dam for actions exceeding, for example, the safety flood or safety evaluation earthquake. The author has proposed such an approach for some dam projects in the past, but the dam owners and engineers as well as the authors of dam safety guidelines were not ready for such useful amendments.

6. CONCLUSIONS

Climate change has developed as a key issue among the population and all kinds of scenarios are published in the media, especially in western countries. In this connection the question comes up, how safe are the large dams in view of climate change. Based on the comprehensive review of the hazards that can affect the safety of large dams, the reasons for periodic safety assessment of dams – climate change is one among several others – and the measures to be taken if a dam does not satisfy the current safety criteria, the following conclusions may be drawn:

(1) For the design and safety evaluation of large dams, natural hazards, man-made hazards, and site-specific and project-specific hazards must be taken into account.

(2) Climate change causes a multiple of natural hazards as is the case with earthquakes and includes the following, which are very relevant for the safety of dams: flood hazard, mass movements at the dam site, mass movements into the reservoir, floating debris due to high intensity precipitation and surface erosion, and debris flows from mass movements or failure of natural dams in the catchment.

(3) Mass movements and debris flows are critical as they may cause overtopping of dams. Embankment dams are most vulnerable to erosion due to overtopping and in the case of small concrete dams the sliding stability may drop to below the required values.

(4) Debris flows and mass movements will silt up reservoirs, but this is not a safety problem for the dam body. Sediments and floating debris are dangerous if they block the intakes of spillways and/or low-level outlets that are required to release floods.

(5) For the safety evaluation of dams the climate change hazards are not different from the many other hazards. To ensure the safety of dams, safety assessments have to be carried out periodically, e.g. at an interval of say 5 years. In these safety assessments, changes in the hazards, changes in safety criteria and other time-dependent developments must be considered. Climate change is one of these factors, but not necessarily the dominant one. Therefore, during the long lifespan of well-designed, constructed and maintained dams, several safety assessments will be required.

(6) As far as the triggering of mass movements and the failure of natural dams in the catchment area of a dam are concerned, strong earthquakes are more critical than meteorological hazards affected by climate change, so that the earthquake hazard is more important than the effects of climate change. However, surface erosion due to heavy rainfall may wash trees and other items into the reservoir, blocking the spillway.

(7) The effects of climate change – as applies also to the other hazards – must be looked at on a case-by-case basis because each dam project is different.

(8) Instead of designing dams for possible climate change effects in the far future that are obtained from different types of models, which will improved by time, it is recommended to use the current design and safety criteria and carry out periodic safety evaluations. In this participatory approach, the real changes can be followed closely.

(9) These periodic safety reviews will indicate if safety upgrades of dams are required. In the short-term the safety of a dam can be increased by lowering of the reservoir.

(10) Dams with small reservoirs, which could be filled rapidly by sediments from mass movements or debris flows triggered by climate change or earthquakes, should not be built.

(11) The silting up of reservoirs is not a safety problem for embankment dams as this is similar to filling up a corresponding tailings dam. In the case of concrete dams in narrow valleys silting up to about 2/3 of the dam height may also be accepted. However, by silting-up the reservoir rule curves must be adapted.

(12) For a resilient dam, it is recommended to check its safety for loads and actions that are beyond the corresponding safety levels.

(13) No new techniques are required to ensure the safety of dams affected by climate change.

REFERENCES

ACI 318-19 (2019), Building Code Requirements for Structural Concrete, American Concrete Institute (ACI), Michigan, USA

IBC-2021 (2021), International Building Code, International Code Council, American National Standards Institute (ANSI), USA

Wieland, M. (2014), "Seismic hazard and seismic design and safety aspects of large dam projects", invited lecture, Proc. Second European Conference and Earthquake Engineering, Istanbul, Turkey, Aug. 24-29, 2014