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RISK ANALYSIS OF A RESERVOIR AS A VITAL SYSTEM COMPONENT

Abstract

The movement of water in nature is a periodic phenomenon, in contrast, social water demand is more even and less seasonal. Reservoirs are created to compensate for the differences between the source and the demand side. Like all human creations, the reservoir as a potential vital component carries risks with its very existence. This article briefly presents possible risk analysis and risk reduction methods for reservoirs. Safety and risk analysis investigations are extended for the entire life cycle of the reservoir and for the entire lifespan of the reservoir. Based on international experience, it proposes the construction of a continuous monitoring system for the reservoir structure.

Keywords: water, reservoir, safety and risk analysis investigations, monitoring system.

VÍZTÁROZÓ, MINT LÉTFONTOSSÁGÚ RENDSZERELEM KOCKÁZATELEMZÉSE

Absztrakt

A víz mozgása a természetben periodikus jelenség, ezzel szemben a társadalmi vízigény egyenletesebb, kisebb szezonalitást mutat. A forrás és igény oldal közötti eltérés kiegyenlítésére víztározókat alakítunk ki. Mint minden emberi alkotás, így a víztározó is, mint lehetséges létfontosságú rendszerelem létezésével kockázatot hordoz. A cikk röviden bemutatja a víztározók lehetséges kockázatelemzési és kockázatcsökkentési módszereit. A biztonságtechnikai és kockázatelemzési vizsgálatokat kiterjeszti a víztározó teljes életciklusára és élettartamára. Nemzetközi tapasztalatok alapján javaslatot tesz a víztározó műtárgy folyamatos ellenőrző rendszerének felépítésére.

Kulcsszavak: víz, víztározó, biztonságtechnikai és kockázatelemzési vizsgálatok, ellenőrző rendszer.

1. INTRODUCTION

Water is an essential element of our very existence. Nowadays, more and more attention is focused on ensuring the security of water and food supply. With the ever-growing demand for water, water is no longer a worthless, unrestricted free resource in much of the world. Due to the rapid increase of the demand for water, the water shortage in more and more areas can only be addressed through very complex water replenishment. It is also a major challenge in case of fighting against wildfires [1], especially during high fire danger periods [2]. The movement of water in nature is a periodic phenomenon, in contrast, social water demand is more even and less seasonal. In order to compensate the differences between the source side and the demand side, different water storage and water retention methods have been created, and one form of these methods is the storage of surface waters. Its works of art are reservoirs of various shapes and functions. New test methods (horizontal sorption) of water absorption by porous stone surfaces and effect of surface treatments have already been implemented [3].

The creation of technical facilities for storage, the maintenance and operation of storage facilities, and the utilization of water require significant production efforts [4]. Water storage makes it possible to satisfy water demands that change over time, and to replenish water resources. This is a good way to intervene against the unfavorable distribution of water resources. Water storage also provides protection against water damage and can help meet the ever-growing energy demand.

2. RESERVOIR RISK ANALYSIS

A reservoir is connected to its natural and artificial environment of varying strength in space and time. This relationship system is shown in Table 1.

The effects between the elements of the connection system pose different levels of risk to the individual system elements, including humans. The main purpose of risk analysis is to identify and classify risks to individuals, groups of people and society. Parallel to the human risk analysis, the analysis must also be performed for ecological and technical (production, service) systems.

RESERVOIR CONNECTIONS (OF VARYING STRENGTH IN SPACE AND TIME)		
Connection to the catchment area	*Water utilization from the reservoir*	*Water utilization in the reservoir*
-geological-topographic -hydrographic, water network -meteorological, climatic conditions (precipitation, temperature, wind, evaporation, ice conditions waving) -natural conditions (plants - animals) -ecological territory -land uses (industrial - agricultural - transport - infrastructural - residential, settlements)	-drinking water -energy production -industrial process water -agricultural, irrigation -flood storage (delay) -water replenishment (at lakes) -water reservation	-wellness, sports - holidays -fishing -heat exchange (cooling) -agriculture, fish, aquatic poultry farming, reed, etc.

Table 1: Connection system of reservoirs

2.1. Risk-based Approach

In the case of water reservoirs - as potential vital system components [5] - the origin and development of the risk-based approach can be traced back to the continuous development of engineering sciences, to the changing political and social demands and to the economic efforts. Numerous international and national studies examined the reasons why reservoir owners switched to risk-based operation. The studies highlighted the following:

- As reservoirs age, dams are less and less able to meet current technical and legal requirements, especially in the event of floods and earthquakes [6].
- People are more and more informed about natural and man-made disasters and dangers, and at the same time there is a growing social demand for safer systems [6], [7].
- The authorities and the government are trying to meet this need, resulting in increasingly stringent regulations [7], [8].
- Frequent changes of ownership of reservoirs and related companies pose a serious problem in operation, as in many cases the new owner is not aware of the basic safety requirements - what's more, does not even know the technology adopted - which also creates the need for risk-based operation. Despite the increasingly strict regulations, the proportion of occupational safety inspections in Hungary is negligible (under 2%) and in addition to this fact, these inspections indicate a very high proportion of workplace malpractice [9].

Uncontrolled processes resulting from the damages of reservoirs can result in a complex emergency, where several components must be investigated and addressed:

- Economic impact: this includes the costs of emergency response, the costs of reservoir restoration, the reconstruction costs, penalties imposed by the authorities and claims for damages.
- Environmental impact: the material escaping from the reservoir spreads over a large area, destroying everything, causing a lasting environmental impact. Additional problems can be long-term effects such as landslides and soil instability (including erosion).

- Social impact: it is easier for the public to accept continuous, occasionally smaller risks, but overall resulting in great damage (e.g., accidents), than one greater risk resulting in smaller damage. In the event of an accident, therefore, negative criticism and pressure from society and politics must also be taken into account.

During the analysis, the risk of reservoir damage for various reasons can be calculated by the following equation[10], [11]:

$$\mathbf{R = P * C,} \qquad (1)$$

where R: risk;

P: probability (probability of the most serious event);

C: the severity of the consequence.

According to another definition of risk, it can be defined as follows [10], [11]:

$$\mathbf{R = V * Th * (C_S + C_L),} \qquad (2)$$

where V: vulnerability;

Th: threat;

C_S: severity of short-term effects;

C_L: severity of long-term effects.

2.2. Risk Elements

The risk factors for a reservoir as a potential vital system component can be given below [11]:

a, Hazard Types

- material and energy, i.e., the way the stored water enters the environment (outflow);
- damage to the reservoir as a technical facility;
- operative failure, resulting in insufficient supply;
- inspection error;

- secondary environmental and pollution effects, damages;
- direct man-made damage (health, material, non-material, terrorist sabotage, revenge).

b, Endangered, affected

Primarily endangered, affected:

- water production technology system,
- employees,
- people living and working in the vicinity of the reservoir, and the citizens temporarily staying there;
- buildings, structures and the built environment;
- infrastructure elements and service users;

Secondarily endangered, affected:

- stockpile, material goods, agriculture (arable land);
- means of production, means of transport;
- environmental elements (air - water - soil and geological medium);
- environmental systems (ecosystems).

c, (Estimated) extent of hazards

In general, the failure of reservoirs and severe damage is a rare occurrence, but the impact and damages are usually significant for those affected.

When designing a new water storage facility, it is simpler to apply the risk-based approach than in the case of an existing facility that is not built to the current technical level. In line with this approach, the following elements should be taken into account during the design process:

- Design/construction: safety and robustness must be sought in case of the structure.
- Safety: can include all passive and active safety features that increase the sense of security for employees and for the public.

- Monitoring and control system: allows for early warning, i.e., the timely detection of abnormal effects and conditions leading to an emergency.
- Maintenance program: includes periodic inspection and repair of dams, drainage systems, equipment and access routes.
- Management system: includes regular inspections, training and retraining of employees, reporting to the authorities and insurances.

A reservoir (just like industrial activity) has a life cycle that consists of design - construction - operation - closure - reclamation (restoration) and the associated control processes.

Safety and risk analysis investigations (Table 2) shall be performed for the entire life cycle of the reservoir and for the entire lifespan of the reservoir [11].

ELEMENTS OF THE LIFE CYCLE **[PROPORTION OF CYCLE]**	**ASPECTS OF ANALYSIS AND RESEARCH**
Site selection, preparation - planning [1-2%]	-examination of a sufficient number of alternatives, completeness of selection criteria, -careful site selection investigations (engineering geological investigations); -thorough site preparation (full inventory of environmental and social aspects); -continuous control of plans, revision as necessary; -designer responsibility, enforcement of quality assurance standards; -preparation of safety and health and safety regulations; -approval of plans;
Construction, execution of works of art [2-5%]	-continuous technical inspection of the construction; -the role of the responsible engineer, compliance with the documentation system and construction regulations, quality certificates; -issue a certificate of the work of art; -implementation plans, documentation and documentation storage in an adequate number and at an available place;

	-preparation of protection plans; -obtaining operating licenses
Operation (possible expansion) [90% (60-75%)]	-specification of compliance with operational and technological regulations; -compliance with safety and health and safety regulations; -continuous barrier, environmental and water quality control, operation of the safety technology (monitoring network) system; -providing documentation (verifiability, probative value);
Liquidation, closure [25-35%]	This element, when measured on a human scale, does not usually occur under realistic conditions. This step is the fate of technically unfortunate reservoirs that do not meet the original purpose of water storage. (e.g., water leaks from the reservoir, the reservoir is ruined, the dam is broken, or it is uneconomical or impossible to restore, etc.) -preparation for closure; -closure and restoration according to official regulations; [-possible recycling or dismantling] -Operation of the post-monitoring system.

Table 2: Safety and Risk Analysis Studies

By their very existence, reservoirs have an impact on their environment. With the exception of design, all elements of their life cycle have an impact on the environment. By environment we mean the environmental elements (air - water - geological medium, soil and rocks), the environmental systems (ecosystem, landscape), the built environment and, above all, people (the affected community).

What are the dangers of operating a reservoir? It is advisable to divide the possible events into two parts. On the one hand, there are events that do not extend beyond the plant area, and there are events that also cross the boundary of the plant area. The first group includes operational events, which can cause damage mainly due to loss of production, such as:

- Failure of water lifting equipment;
- Failure of storage auxiliary systems;
- Minor damage to dams that does not involve material release (leakage) but requires repair;
- Failure of water treatment equipment;
- Accidents at work.

The second group includes so-called accident events such as:

- Delivery of harmful pollutants and sediments to the reservoir from the catchment area and from the inflows;
- Flood and reservoir water level control error;
- Slipping - breaking of the dam, significant mechanical damage;
- Failure of the dam, complete destruction;
- Strong destruction on the downstream side (primary, secondary effects) due to dam damage;
- Serious accidents at work.

It can be seen that in the case of incidents limited to the work areas, personal injuries are only caused by accidents at work, while the impact of emergencies beyond the work area can endanger the population and the employees, either directly or indirectly. When designing and operating a system, these hazards must be taken into account in the first place and the safety system must be optimized to avoid them.

2.3. Risk Evaluation and Risk Assessment

In order to accurately identify the risks, it is absolutely necessary to have the operating and connection scheme of the system, which usually includes several maps, plans and detailed drawings. There are several methods for inspecting reservoirs from a risk-based approach, using different risk assessment and risk management methods. Basically, these methods can be classified into two groups. The first group includes methods that perform detailed risk analysis (e.g., safety analyses, vulnerability analyses), and the second group includes methods based on risk indexation (e.g., indexation based on safety priority).

2.3.1. Detailed Risk Analysis

The method based on detailed risk analysis has been developed specifically for reservoir dams and provides guidance to their owners, operators and safety professionals. One of these methods is the so-called PRA (Portfolio Risk Assessment) method, which examines six factors [12]:

- Define objectives
- Define requirements of the analysis (security of supply, etc.)
- Perform engineering assessment of the reservoir and dams
- Conduct risk assessment of the reservoir
- Conduct risk assessment of risk reduction
- Risk assessment of the analysis results

It can be seen, that also based on this method, the safety of the reservoir dams is based on an integrated concept, the elements of which are as follows:

- Structural safety:
  - Geology- and geotechnics-based design criteria;
  - Hydraulic based design criteria;
  - Earthquake-based design criteria;
- Monitoring:
  - Continuous monitoring of the reservoir structures and the water quality;
  - Periodic safety screening;
- Safety of operation and supply:
- pplication of real reservoir operation (water quality) standards in basic situations and in situations with increased hydrometeorological risks;
  - Preparation, training and exercise of employees;
  - Periodic maintenance;
- Emergency planning:
  - Emergency response plan (internal and external protection plan);
  - Emergency alarm systems;
  - Evacuation plan, provision of escape routes.

Steps of the applied risk analysis:

- Defining failure modes;
- Defining the starting (peak) event;
- Setting up a system fault tree;
- Modeling the behavior of each component;
- Determination of the relationships between the failure of elements and failure modes;
- Calculation of probabilities and correlations;
- Calculation of system failure and availability.

The method can also be used to determine the location and the required amount for forecasting instruments, sensors, cameras and engineering barriers, and the effectiveness of protection [11].

2.3.2. Indexation Method

It is a less objective method, but the so-called risk indexation method gives faster results. The essence of this method is that it focuses on the physical condition of the facility and derives the risks based on it (this is the opposite of the method described above, where the condition of the facility has been assigned to the risks). According to the method of Andersen and Torrey [13] the vulnerability can be determined from the basic parameters by the following indexing method:

$$\mathbf{V = (I_1 + I_2 + I_3 + I_4)/4 + (E_1+E_2)/2 + (D_1+D_2)/2,} \qquad (3)$$

where I: time independent variables — I_1: height of the dam

I_2: type of the dam

I_3: type of foundation

I_4: storage capacity

E: external time-dependent variables — E_1: age of the dam

E_2: seismic activity of the area

D: reservoir design parameters — D_1: runoff capacity

D_2: mass flow factor

These parameters are rated on a scale of 1 to 10, the higher the value given to each parameter, the greater the vulnerability and thus the inherent risk.

Perhaps one of the most important outcomes of risk assessment is the drafting of so-called flood maps. It is also useful for disaster management in case of flood management [14]. The most critical event of the reservoir is the occurrence of a failure of the dam through the full cross section at one point of the dam, since the liquid behind the dam (water + sediment) floods the areas below the dam (downstream) through this gap. Flood maps are created based on modeling of these events. These maps show which areas are at risk and where plans need to be drawn up to alert and rescue the population.

2.4. Risk reduction methods applicable for water reservoirs

In the knowledge of the risks or hazards, risk reduction measures can be developed, which can be of engineering-technical or administrative nature. The cost-effectiveness of these steps is then determined and, if feasible, these are included in the business plan of the reservoir owner or operator.

The number of risk factors is large, forming a complex, coherent system. The characteristics of functions calculating risks are difficult to define and estimate. Determining the probability of occurrence of each event can be critical in calculating risk. During process analysis, causal relationships need to be explored, the determination of and/or relationships (for example, in fault tree analysis) is an important factor in the calculations. It is advisable to show the effects of the risk elements on maps of different scales depending on the expected spatial extent of the effect; these maps should show the safety and risk zones, the endangered objects, infrastructure elements, as well as the extent and location of the expected damage [15]. Some pre-planned organization, protection objects, and rescue and supply (logistics) routes may be also depicted here.

At reservoirs, the impacts and risks of events arising from non-normal operating activities can be grouped as follows:

- phenomena resulting from the deterioration of structural integrity (malfunction of the reservoir dam and its structures, failure of the dam) and their effects (release of stored water into the environment, flood);
- effects of incorrect operation (overfilling, lack of maintenance, deterioration of technical condition, etc.);
- effects of other risk factors (e.g., incidents, meteorological events, impacts, infections, etc.).

Attention must also be paid to the special risk elements in the reservoir and the plant serving it (waterworks, etc.):

General risk factors:

- electricity (high voltage);
- combustible gases, solid and liquid energy sources;
- compressed air;
- thermal energy;
- technological and wastewater;
- Risks of a special plant or equipment;
- Specific technological risk factors:
- risk of fire and explosion [16];
- hazardous (corrosive, irritant, toxic) chemicals;
- storage at heigh places;
- biological agents;
- radioactive substances (ionizing radiation or natural background radiation);
- energy emissions;
- release of pollutants into the environment;
- Risk of pipeline burst;
- Risk of downtime (emergency shutdown, restart, pressure surges, etc.);
- Risk of natural forces:
    - meteorological effects (extreme precipitation, wind, temperature);

  - storm, windstorm, downpour;
  - flood, inland water;
  - surface movements (collapsing, sinking - slipping - sliding, cavitation, etc.);
  - other geotechnical damages (earthquakes, geological events, etc.);
- lability damages (material - non-material):
  - terrorism [17], [18];
  - damages resulting from the physical - chemical - biological properties of the product;
  - environmental pollution,
  - fire and explosion;
  - infections;
  - other incidents.

Safety and health risk analysis tests shall be performed for the entire life cycle of the reservoir and for the entire lifespan of the reservoir [17], [19]. In risk reduction, it is also worth placing more emphasis on active fire protection solutions for service plants and their efficiency [20].

3. SUMMARY AND PROPOSED CONTROL SYSTEM

The movement of water in nature is a periodic phenomenon, in contrast, social water demand is more even and less seasonal. Reservoirs are created to compensate for the differences between the source and the demand side. Like all human creations, the reservoir as a potential vital component carries risks with its very existence. This article briefly presents possible risk analysis and risk reduction methods for reservoirs. Reservoir dams require continuous monitoring, which can be done by continuous and periodic measurement of various indicator characteristics [4]. This monitoring system ensures that the environmental impact of the dam is minimized and that catastrophic situations are avoided. It is recommended to have a control system at both abandoned and still operating reservoirs. Based on international experiences [21] it is advisable to operate a control system consisting of the following elements (Table 3) at a reservoir, where it is recommended to connect all sensors directly to the dispatcher service [11].

THE MEASURED INDICATOR AND IT'S FUNCTION	INSPECTION FREQUENCY
1. Visual inspection	
o inspection of the surface of the dam; o taking leachate and sediment samples for laboratory testing if necessary; o report on the detected situation.	Every day Once
2. Observations related to Waters	
o water level, in the reservoir, measurement of monitoring wells (monitoring of groundwater level); o measuring the rate of flow of water sources (seepage) regularly flowing out of the dam body and ordering any intervention.	Quarterly (Continuously in critical cases)
3. Regular geodetic and geotechnical examination of the movements of the dam body (deformation measurements)	
o at regular intervals, on the planned measurement network, geodetic coordinate determinations and evaluation of data according to movement examination criteria; o performing regular measurements with an inclinometer on the installed measuring network and evaluation of the data (possibly placing automatic displacement meters at critical locations); o regular recording of pore water pressure values (with continuously recording automatic measuring devices) on the installed measuring network and evaluation of the data.	Quarterly
4. Measurement of meteorological elements	

o with an automatic measuring station that measures critical meteorological elements (temperature, precipitation, precipitation intensity, wind characteristics, etc.).	Every day, continuously
5. Registration of seismic (dynamic and seismic vibrations) phenomena	
o with an automatic measuring station, recording of dynamic effects (traffic, transport, effects of various material rearrangements, etc.) and micro-seismic phenomena at critical locations.	Every day, continuously

Table 3: Structure of the control system

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