Risk analysis of the Kaunas hydropower system

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Abstract

This paper presents risk analysis of the two biggest hydrological objects in Lithuania – Kaunas Hydropower Plant (KHP) and Kruonis Hydro Pump Storage Plant (KHPS), which comprise Kaunas hydropower system (KHS). Kaunas HP risk analysis was performed and the impact on it of the Kruonis HPS upper artificial reservoir crash during the floods period was analysed. Also the Kaunas dam overtopping probability and consequences of dam failure evaluation in terms of Kaunas city flooding zone mapping were evaluated. For the Kaunas dam probabilistic safety analysis the fault and event tree structures were used and dam overtopping probabilities under several scenarios were evaluated. For the calculated results sensitivity analysis was performed. The analysis results were used to specify the evacuation plans in the case of a catastrophe.
Keywords: hydropower system, artificial reservoir, fault and event trees, flooding zones, consequences.

1 Introduction

According to the world's summarized statistics [2], 34% of dam break causes is overtopping and 30% instability of foundation. This confirms that dam failures can occur because of their inability to safely pass flood flows. The hazard can be even more important in the case of an upstream dam break. In Lithuania there are two large hydrological objects where such a hazard has to be investigated and evaluated, more over they depend on the one system.

The purpose of the work is to perform risk analysis for the Kaunas hydropower system, which consists of the Kaunas Hydropower Plant and

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Kruonis Hydro Pump Storage Plant. It is necessary to estimate the Kruonis HPS influence on the Kaunas HP safety in the case of its upper artificial reservoir breaking and the hazard to Kaunas city of flooding in the case of a KHP dam break. Figure 1 presents the scheme of the Kaunas hydropower system.

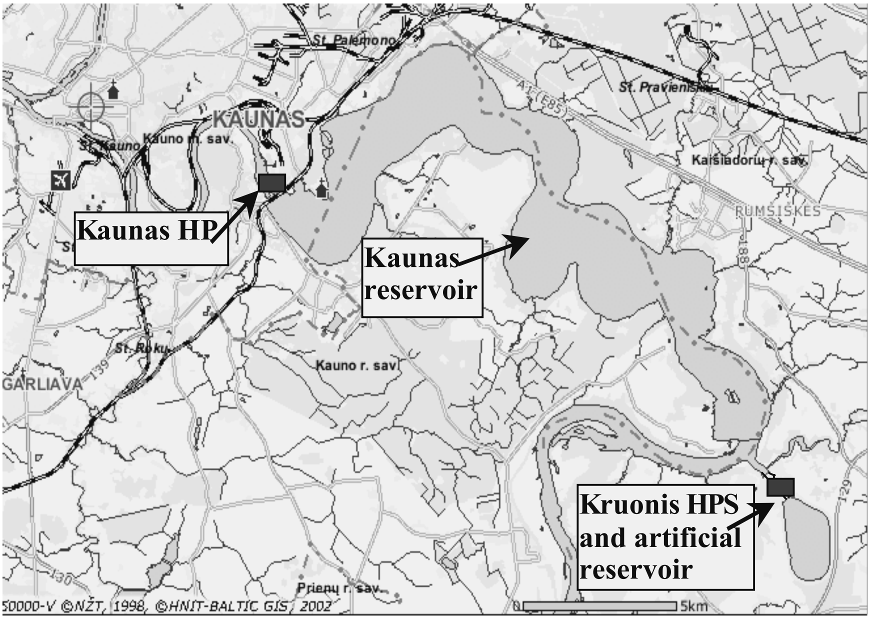

Figure 1: Kaunas hydropower system.

Kaunas HP is situated on the biggest Lithuanian river Nemunas, upstream of the city of Kaunas, with a population of over 400 thousand. KHP total installed capacity is 100.8 MW, it has four turbines and three spillways.

About 26 km upstream of the KHP, the Kruonis HPS is located, with an installed capacity of 600 MW. KHPS takes water from the Kaunas reservoir of 462 million m^3 to its artificial concrete reservoir with a storage volume of 49 million m^3. The operation of KHPS causes water-level fluctuations of about 0.07 – 0.21 m in the reservoir.

2 Probabilistic safety analysis of KHP dam

The Kaunas HP accident, which would bring the biggest hazard for the Kaunas city, is that the Kaunas dam breaks during the flood period. After potential initiating events analysis the probabilistic model was based on hydrologic failure modes analysis. The determination of some modes was based on international experience, as there were no available dam data, and on some KHP reports about deterioration of construction material and slope instability.

2.1 Analysis of initiating events

Initiating events are categorized as internal and external. For representing the initiation events the fault/event trees were used. The following initiating events for KHP were identified and analysed: 1) dam body ageing and internal erosion; 2) floods (extreme inflow to reservoir); 3) Kruonis HPS artificial reservoir break.

The evaluation of the dam body ageing and internal erosion requires monitoring data and is a complex analysis of many factors. In this work reports were used of body monitoring and issues of the Lithuanian Agriculture University. The reports claim that the dam body is in a good stage and there are no significant symptoms of ageing and internal erosion due to long-term exposure of loads causing changes in the structural integrity of the dam and its foundation. Therefore, according to generic statistics and judgmental estimation, it was assumed that the probasbility of dam break due to general dam body erosion is 3.1E-06 [1].

Evaluation of failure of spillways and gate operation could be based on equipment failure statistics. All KHP records of failures and maintenance reports of the following equipment were analysed: 1) spillway gates; 2) gate opening cranes; 3) electricity source; 4) auxiliary electricity source for cranes –diesel generator. Due to poor failure statistics of this equipment, the values were evaluated on judgmental experience and taken from generic statistics [2].

Flood inflow is an initiating event, which consists of hydrologic conditions with flows above the normal. A big amount of flow data was available from Nemunas upstream measurement stations: everyday flow data from 1920 until 1996. Flow data statistical analysis was performed, Kaunas dam overtopping probabilities evaluated [3], and later probabilistic extreme floods models developed [4], which let us use extreme flood occurrence probabilities for the present study. Basically spring floods were analysed, which have the biggest influence on the dam safety, and the different significant extreme flow values were chosen for the model input, which are presented in section 2.2.

Snow melting and heavy rains can cause a big flow to the Kaunas reservoir. After Kruonis HPS operation a big debate started about the plant impact on the reservoir level fluctuations and its potential hazard to Kaunas dam. What is the level of the risk in the case of KHPSP artificial reservoir break? The analysis of this problem is presented in section 3.

2.2 Fault and event trees

The analysis of the initiating events revealed that the most probable dam failure could occur due to hydrological loading: extreme floods. Moreover, the extreme floods bring danger if dam equipment, which discharge water thorough the dam, fails. Any equipment failure does not bring danger under the normal water level conditions, as it could be fixed immediately. Therefore this paper analyses the sequence of functional events when extreme flooding occurs. Event tree and failure tree analysis helps to construct the logical scheme of the sequence. For the analysis of event and fault trees the Risk Spectrum software was used.

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From the flood analysis three different flood flows were analysed, which are dangerous for the dam under the different conditions. The initiating event values and probabilities are presented in table 1.

Table 1: Probabilities of initiating events.

Flow m^3/s	Probability
1700 – 2710	7,40E-02
2710 – 3740	5,80E-03
over 3740	4,10E-04

Constructing the event tree the following functional events were analysed: 1) failure to observe and act; 2) gates drive failure; 3) gates state; 4) gates fail; 5) gates blocked by debris. The consequence event is dam overtopping.

The event “failure to observe and act” represents the important chain of events leading up to operational actions. In the early spring, Near Kaunas dam, the water level has to be decreased to a nominal level (40 m) and it is necessary to prepare for the potential spring floods. In order to avoid an accident the three main chain elements have to be performed: 1) observe initiating event; 2) communicate to those who need to know about the observation; 3) take appropriate actions. In the process of the chain development various mistakes can occur as this category primarily covers human error. To evaluate human error is difficult and for the analysis we used world established human error probabilities [2].

“Gates drive failure” event represents the condition that the operational equipment to raise the spillway gates fails to function properly. If the failure occurs, the instantaneous “gates state” is analysed: how many gates were opened until the drive fails. In the KHP usually it is enough to raise 2 gates in order to keep water under the maximum available water level (45.6 m). For that purpose the plant uses two electrical cranes: the main and auxiliary crane. The system fails if all components of the system fail. For the analysis of the gate drive failure the fault tree was constructed.

“Gates state” event also is analysed if the operator fails to observe and act. The frequencies of opened 1, 2 or 3 gates (table 2) were evaluated using KHP notes about frequency of gate raise.

The gate drive system may work properly, but there can arise problems with gate mechanisms inside (seizing, freezing, release from rising system, etc.). The “gates fail” probabilities, presented in table 2, were calculated using international one gate failure statistics and a fault tree: the three different possibilities of one, two, three gates failing were considered [3].

The branch “gates blocked by debris” covers the possibility of excess debris and floe coming into the reservoir building up and blocking the capacity of the spillways. According to KHP reports there was no single event of spillway blocking, therefore the international statistics of the event was used [2].

Analysing “dam overtopping” case, the accent is put on the hydrological impact of dam break, so the primary extreme flood consequence is dam

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overtopping. The dam overtopping means the water level reaches 48 m and starts to flow over the top of the dam.

When an initiating event begins and all safety barriers act properly and the overtopping does not occur, the event tree results in a “safe dam” top event.

For analysing the causes of failure of safety barriers fault trees were used. The analysis was performed for gate drive failure and gate failure. The fault tree for gate drive failure concentrates on the failure of primary drive system and its secondary backup system. The gate failure fault tree represents the various combinations of failures that could result in one, two or three gates failing.

The probabilities used for fault and event tree analysis are presented in table 2 and the dam overtopping calculation results are presented in table 3.

Table 2: Probabilities of the fault and event tree elements.

Description	Probability
1 gate opened	1.8E-01
Emergency power failure	3.0E-03
Offsite power failure	1.0E-03
Gates drive failure	1.0E-04
Operators failure	1.0E-04
Main crane failure	3.0E-04
Auxiliary crane failure	3.0E-03
One gate failure	1.0E-02
Gates blocked by debris	1.0E-05

Table 3: Dam overtopping probabilities under three scenarios.

Initiating event magnitude, m^3/s	Overtopping probability
1700	1.29E-05
2710	2.96E-06
3740	1.23E-05

The gate drive and gate failures probabilities are not evaluated from failure statistics, therefore the sensitivity analysis of the dam overtopping has to be performed: which elements of the fault and event trees have the biggest impact on the result. Analysing dam overtopping probability sensitivity due to gate failure and gate drive failure revealed that increases or decreases of failure probabilities do not make significant impact. The results of primary event and fault tree parameter sensitivity analysis are presented in table 4. The results indicate that initiating event (extreme flood) probabilities have the biggest impact on dam overtopping probability estimation. The other system components to which dam overtopping probability is sensitive are crane railing failure and operator’s mistake. This concludes that attention has to be given to maintenance of the gate drive system and gates, because to control initiation events is rather impossible, they can only be predicted.

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Table 4: Sensitivity analysis results of ET and FT parameters.

Functional events (1)	Maximal overtopping probability (3)	Minimal overtopping probability (4)	Proportion of (3)/(4)
Extreme flow 3740 m^3/s	1.38E-04	1.71E-05	8.07
Crane railing failure	8.68E-05	2.22E-05	3.91
Operator's mistake	8.68E-05	2.22E-05	3.91
One gate failure	7.54E-05	2.34E-05	3.22
Gates blocked by debris	3.53E-05	2.74E-05	1.29
Offsite power failure	2.99E-05	2.79E-05	1.07
Main crane failure	2.86E-05	2.80E-05	1.02

3 Dynamic flood modelling

This section presents two models of dynamic flood modelling: the Kaunas reservoir wave model after Kruonis HPS artificial reservoir crash and the second is related to the wave model downstream of the Kaunas PH after Kaunas dam crash. The analysis goal is to estimate KHPS artificial reservoir crash consequences on the KHP dam if it could cause the domino effect and destroy all the Kaunas hydropower system.

3.1 Kruonis HPS artificial reservoir crash impact on Kaunas dam stability

The analysis covered the assumption that Kruonis HPS artificial reservoir could crash only if it is full of water. All possible initiating events were analysed, which could cause this accident; two most important appeared: 1) the deformation of embankment base and slope, sliding; 2) erosion of reinforced concrete supporting walls of the reservoir.

In order to evaluate the possible Kruonis HPS artificial reservoir water flow to the Kaunas reservoir, the laboratory of Hydrology [5] created an imitative model. The main assumption was that the reinforced concrete walls collapse and a hole of three blocks (25 m lengths each) forms. The water amount of 45.8 million m^3 flows to the Kaunas reservoir and forms a flood wave, which is moving towards Kaunas dam. For modelling the hydrodynamic model MIKE 21 was used. Several scenarios of reinforced concrete wall collapse were analysed.

The modelling results revealed that the highest wave near the Kaunas dam would be 0.75–0.92 m, and the wave front would reach the dam in about 20–60 min from the beginning of the KHPSP reservoir crash. Under the normal conditions such water level rise near the dam would not cause any harm, but during the floods, when the water level near the dam is 45.6 m or even more, the additional water amount could additionally load the water-development works

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and cause overtopping or even dam crash. But the probability of such an event is very low, because the Kruonis HPS reservoir crash is hardly possible.

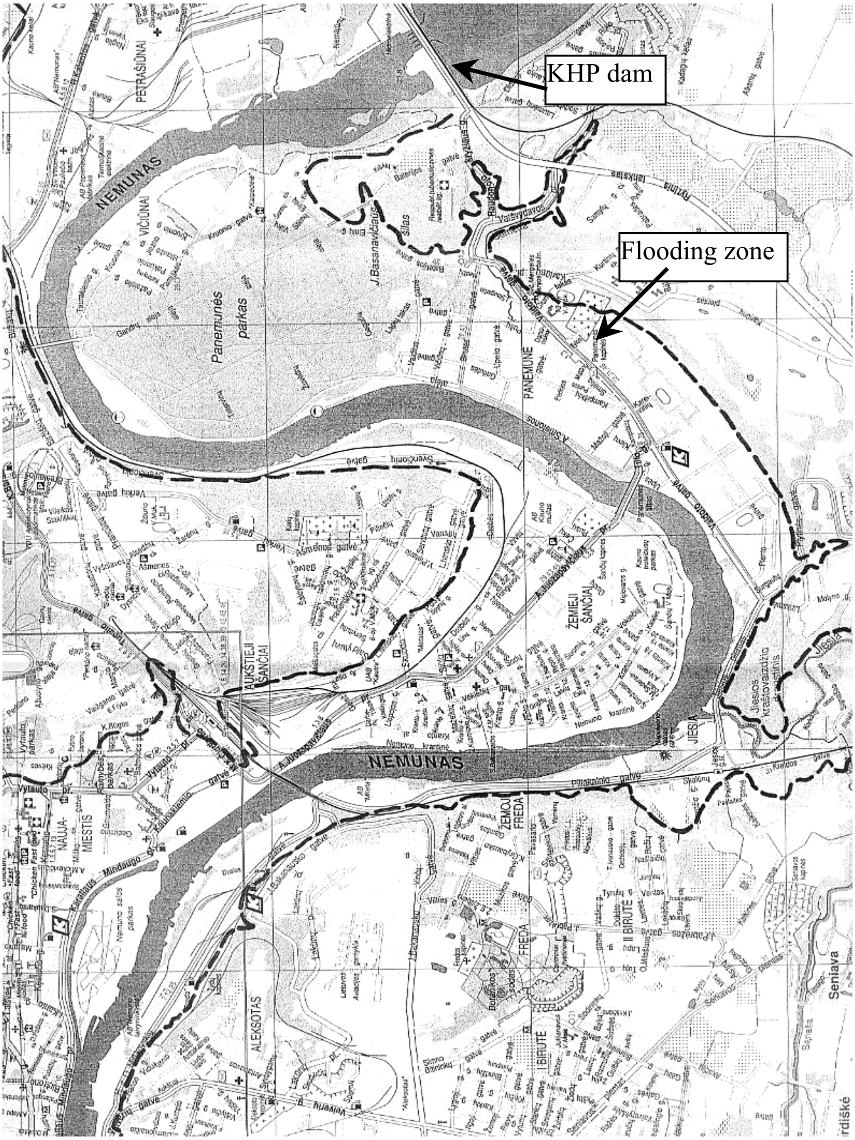

Figure 2: Maximal flooding zone of the main Kaunas city part.

In the case when the water level in Kaunas reservoir reaches the maximal limits, the upper Kruonis reservoir crash can cause Kaunas dam overtopping. Therefore it was decreed that for risk minimization, the water level in KHPS

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artificial reservoir has to be minimised (about 10 million m^3) before the spring floods or if the water level in KHP reaches 44.8 meters.

3.2 Kaunas city flooding model

Kaunas city, as it was mentioned, is on the river Nemunas just downstream of the Kaunas dam. The dam break would bring much harm to the city and many lives could be lost. The aim of this part of the analysis is to indicate the city flooding zones if the dam breach occurs.

The dam break primary analysis was performed in 2000 [6]. The main model assumptions were: 1) the breach dimensions: in the top 70 m, in the bottom 42 m; 2) the breach opening time: 2 hours; 3) inflow to reservoir: constant 3000 m^3/s;

The following results were obtained: 1) flood wave front arrival time at defined cross-sections; 2) water stage and flood hydrograph at defined cross-sections; 3) flood crest profile and maximum flood discharge along the downstream river. As the consequences are generally evaluated by determining the path and extent of the resulting flood wave, using the modelling results the flooding zones were drawn on the map. Figure 2 presents the maximal flooding zone (lined curve).

4 Risk evaluation for the Kaunas city

The risk analysis for Kaunas hydropower system was performed and its potential harm to the city evaluated. Moreover, the analysis was complemented by Kruonis HPS artificial reservoir break, which revealed that the consequences would not increase significantly.

The flooding zone mapping revealed that the flooding area occupies about 24 km^2 of the Kaunas city central part. The population in this zone is about 130,000. Evaluating the dam break and flood wave routing time, the consequences could be ranged [7] as follows:

1) Consequences to human health and lives: catastrophic. The catastrophe can result in a conceivable number of deaths, many injured people.

2) Consequences to nature: catastrophic. Significant amount of tainted water from urban regions would touch the environment.

3) Consequences to the tangibles: catastrophic. Residential houses, commercial and manufacturing buildings, transport would be damaged or destroyed. The big costs for cleaning and fixing works will be needed.

4) Due to the high speed of flood spread, the large part of the population living in the nearest dam districts will not be able to be evacuated.

Probabilistic risk analysis includes the probability as an integral analysis tool. Taking it a step further is a risk assessment, which comprises a total process; it uses risk analysis to look at all risk factors and incorporates the use of costs and benefits as well as social acceptability in evaluating risk. The results of this analysis will provide useful information for preparing evacuation plans and other

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necessary action in case of catastrophe, and also evaluating necessary investments for safety tool development.

5 Results and conclusions

The probability of KHP dam overtopping, under the extreme flow 3740 m^3/s scenario was evaluated to be 1.23E-05. The general dam overtopping probability was evaluated to be 2.81E-05. Input probabilities used in the analysis are without doubt the largest source of uncertainty for the analysis results. Sensitivity analysis revealed that the dam overtopping probability is sensitive to the extreme flow probability, crane railing failure and operator's mistake probabilities. This reveals the biggest attention has to be focused on maintaining the crane railing system, as the course of extreme flow and human error mistakes is rather impossible. The automation of an alarm system should decrease the possibility of operator mistakes.

In the case of KHP dam break, the flooding zones were determined. The mapping zones and the wave front arrival time analysis results were submitted to the Department of Civil Safety of Kaunas city for specification of catastrophic event evacuation plans.

The dynamic flood modelling results show that under normal conditions Kaunas hydropower system is safe. Kruonis HPS crash would increase the water level by only about 0.7 – 1.5 m. If the water level in Kaunas reservoir is nominal, it would not impact Kaunas HP risk.

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