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RISK ANALYSIS OF POTENTIAL FAILURE OF EMBANKMENT DAMS BASED ON FUZZY INFERENCE

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Embankment dams usually are subject of complex endogenous problems closely connected with spatial and temporal relationship of flow occurrences. The design and safety of the dams primarily depend on the accurate prediction and assessment of hydrological input e.g. stream flow and rainfall. Local scale design is used in this study for risk analysis of potential failure. In the most cases for prediction of potential failure the real time of observation and operation is very short and traditional error measures are often encountered in the information data. Fuzzy set theory is used to model the engineering decisions in some specific applications as risk analysis of failure. Fuzzy Inference System (FIS) is recommended with two fundamental characteristics: a) data scarcity with the need to take decision into account; b) complexity and variability of the problem with quantitative and qualitative criteria.

INTRODUCTION

The possibility of potential failure of dams is delimited between two scales: the catchments or large scale planning and the local or small scale design [3]. Because of the short real time of operation and the restricted amount of data the analysis is carried out including possible cases of failure under extreme conditions of a small scale design. The major steps in this study are:

- Identification of undesired events and scenarios;
- Quantification of scenarios;
- Quantification of consequences and acceptable decisions;
- Example.

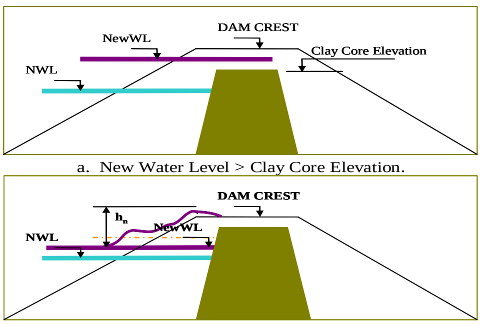
IDENTIFICATION OF UNDESIRED EVENTS AND SCENARIOS

The potential events that may lead to failure are recognized and described by several steps subject to infrastructural or environmental damages, structural damages, instability of the slopes etc. A tree of events is used for characterization of these factors with different branches and nodes. Sample assessment of undesired events is illustrated in Table 1 using a probabilistic risk analysis (PRA) and expert evaluation.

Table 1. Sample of potential events for failure.

Type of event	Description	Assessment
$Q>Q_{probab}$	Rainfall, thawing – high water level	Possible
	Wave in lake from landslide of rock and avalanche	Unlikely but possible: on the right bank a stable landslide exists. An avalanche isn't possible.
	Wave in lake from destroying of upper dams	There isn't wave; throw aside
	Wave in lake as a result of earthquake	Possible. It's subject of special research
High water level and wind	Wind wave	Likely, very possible
Input damages	Obstruct from landslide, overgrown, deposits, silts, avalanche	It's rejected because topographical and geological conditions; No overgrown
	Failure of gates	It's rejected; there isn't gate
Damages in drainage canal	Obstruct: landslide, overgrown, deposits, avalanche	It's rejected because topographical and geological conditions; No overgrown
	Cavitation and erosion, crack in revetment	Subject of individual research
Output damages	Erosion in lower section, crack, loss of coast stability	Throw aside. There isn't observations and data like to.
Dam body damages	Internal erosion, slope instability	Throw aside. There isn' t observations and data like to.

The results from identification of the undesired events and scenarios were screening and some events were rejected. Potential scenarios of failure are shown in Figure 1.



a. New Water Level > Clay Core Elevation.

b. Overflow of Dam Crest by New WLevel and Wind Waves

Figure 1. Two scenarios of dam failure over Normal Water Level (NWL) that are subject to quantification.

QUANTIFICATION OF SCENARIOS

Combinations of two basic events generate two major events for failure- high flood and wind waves. Every branch of the tree could be assessing by combination probability for the

occurrence of event A_i under the condition that event B has already occurred, according to the formula of Bayes:

$$P(A_i/B) = \frac{P(A_i)P(B/A_i)}{P(B)} \tag{1}$$

where $P(B)$ is calculated from the formula of total probability:

$$P(B) = \sum_{i=1}^{n} P(A_i)P(B/A_i) \tag{2}$$

where the total probability $P(B)$ depends on $P(A_i)$ and on the conditional probability $P(B/A_i)$:

- If event B implies event A_i then $P(B/A_i) = 1$.
- If A_i and B are stochastically independent, $P(B/A_i) = P(B)$ and $P(A_i/B) = P(A_i)$; otherwise A_i and B are stochastically dependent.
- If A_i and B are independent, $\overline{A}_i$ and B, $\overline{A}_i$ and $\overline{B}$, A_i and $\overline{B}$ are also independent events.

The tree of events for a tree stage random experiment is given below:

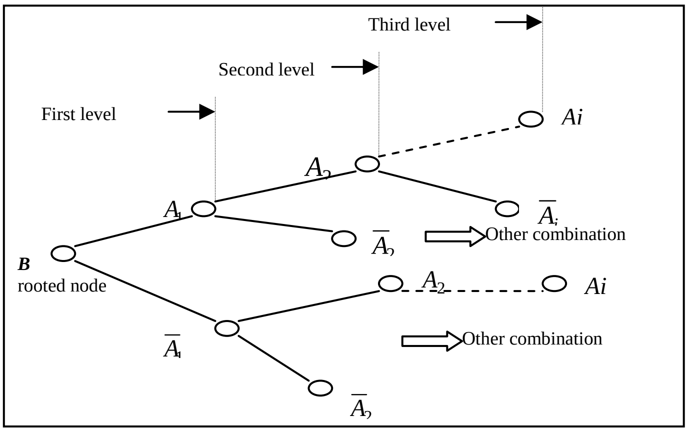


Figure 2. Tree of events: Rooted node for high flood water level is accepted as node ***B.*** Wind waves are described by conditional probability according to formula (1). Rooted node may be branching depending on hydrological events.

Hydrological high water level in dam reservoir

Some statistical methods have been used for example exponential distribution, gamma and Weibull distributions, lognormal distribution etc. The probability density function of random variable X is:

$$f(x) = \lambda e^{-\lambda x} \qquad \text{for } 0 \le x < \infty \tag{3}$$

The parameter λ is estimated by momentum method and monitoring data using the mathematical expectation.

With the estimated value of λ the probability of overflow above the variable *x* is:

$$P(X > x) = \int_x^\infty \lambda e^{-\lambda x} dx \tag{4}$$

Other distributions are calculated in the same manner. For example gamma function is:

$$\Gamma(r) = \int_0^\infty x^{r-1} e^{-x} dx, \qquad \text{for } r > 0 \tag{5}$$

The probability density function of Γ is:

$$f(x) = \frac{\lambda^r x^{r-1} e^{-\lambda x}}{\Gamma(r)} \qquad \text{for } x > 0 \tag{6}$$

The parameters λ, r are evaluated by momentum method using expected value and variance. Weibull distribution is often used the modeling until failure of many physical systems. The cumulative distribution function is:

$$F(x) = e^{-(x/\delta)^\beta} \tag{7}$$

where parameters δ, β depend on the gamma function and the system of mathematical expectation μ and variance σ^2:

$$\mu = \delta\Gamma(1+\frac{1}{\beta}) \qquad \sigma^2 = \delta^2\Gamma(1+\frac{2}{\beta}) - \delta^2\left[\Gamma(1+\frac{1}{\beta})\right]^2 \tag{8}$$

Wind waves

Evaluation of the wind wave characteristics could be done using statistical methods. The wave patterns depend on wave inducting factors - wind velocity, duration, fetch and depth of reservoir. The wave height probability *p%* of the deep water zone is estimated by stochastically hydrodynamic model. The depth decreases, the wave length and velocity decrease too. In front of the dam slope waves break out entirely and run-up ashore. The evaluation of the wave run-up *p%* is determined according to suitable statistical model.

QUANTIFICATION OF CONSEQUENCES AND ACCEPTABLE DECISION

The results of statistical analysis of two distributions and their parameters are illustrated in the Figures 3,4. On the basis of described probabilities risk analysis is estimated using two random events and their conditional probabilities. Probability of failure could be evaluated as conditional probability using formulas (1), (2) and above mentioned distributions accounting the level of clay core and dam crest – see Figure 1:

a. Probability of failure of the dam given that the following condition has already occurred New WL > clay core → with *p(Failure/High WL)=1*;
b. Probability of failure of the dam given that the break Wind Wave (*WW*) and High *WL* have already overtopped the crest → *p(Failure/WW &High WL)=0.5,* using expert evaluation.

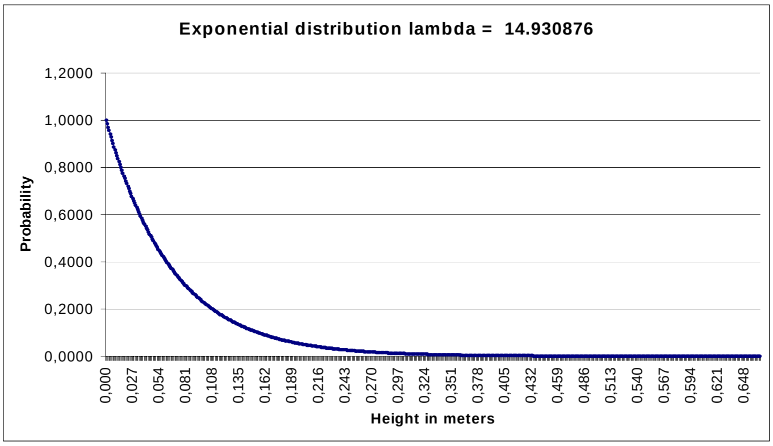


Figure 3. Cumulative exponential distribution in dam reservoir.

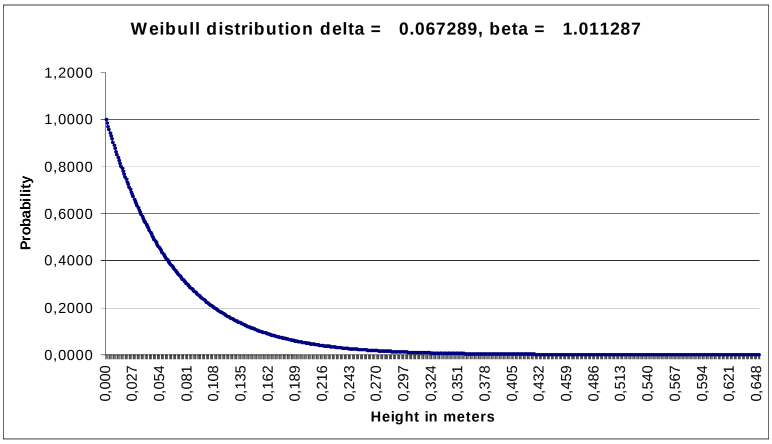


Figure 4. Cumulative Weibull distribution in dam reservoir

Fuzzy inference on the basis of monitoring

The water level at any time step in the local scale design is a function of previous water levels and flood water level as well as of the meteorological, groundwater and wind conditions. This dependency could be expressed by a fuzzy function determined by the nature of the hydrological system being examined. As the water level is a strongly nonlinear

and time varying function (Figure 5), it is difficult to define the relationship. Fuzzy rule-based models could be introduced in this case as a powerful alternative modeling tool using Fuzzy Inference System (FIS) [2,4]. Fuzzy modeling gives the possibility to select the better statistical distribution in some very complicated cases with uncertain parameters [2].

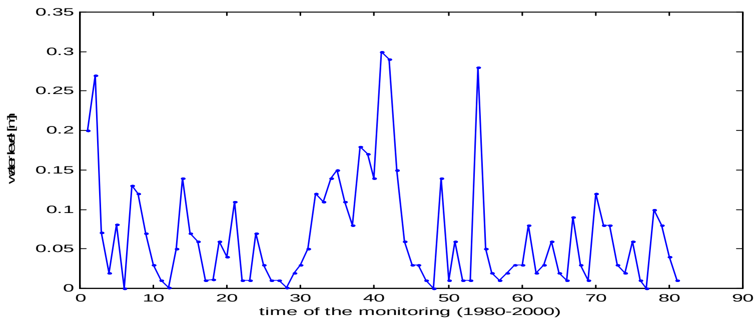


Figure 5. Water level overflow during the observation period

EXAMPLE

An example of rock-fill dam with vertical clay core is considered. The cross section of the dam is shown in Figure 1. The same picture illustrates two of the most important scenarios of dam failure, located on the basis of undesired events identification (Table 1).

Based on water level recording for 20 years period the statistical distribution was estimated. Statistical evaluation of the wind wave parameters is done by methods of Bulgarian Design Code [1]. The wind velocity in the direction of fetch is determined by wind rose for wind design probabilities. Wave height probability *p=1%* and *p=0.1%* of the deep water zone and respectively broken wave run-up on the dam slope various probability (0.1;1;2;5;10%) are calculated according to[1].

Table 2. Probability of dam failure according different scenarios

Type of failure	Probability %		Probability in years
W level > clay core level=336.42 SUM P 4.0639.10-5	**P0** high wave 0.00853	---	$4.0639.10^{-5}$
overtopping of Dam crest SUM P 1.7439.10-4	**P1** high wave 0.01	wind 2 wind waves 0.1	$1.7439.10^{-4}$
	P2 high wave 0.008797	wind 2 wind waves 0.1	$1.2986.10^{-11}$
	P3 high wave 0.008769	wind 2 wind waves 0.1	$6.7648.10^{-11}$
	P4 high wave 0.00853	wind 2 wind waves 0.1 1	$1.4797.10^{-9}$

$$P_{risk}^{max}\, norm = 5.10^{-5}$$

$$P_{risk}^{min}\, norm = 3.10^{-5}$$

Event tree architecture of the failure scenario with combined action of high water level in the reservoir and wind waves are shown in Figures 6. The risk assessment is analyzed for different probabilities of the branches including waves break and creeping.

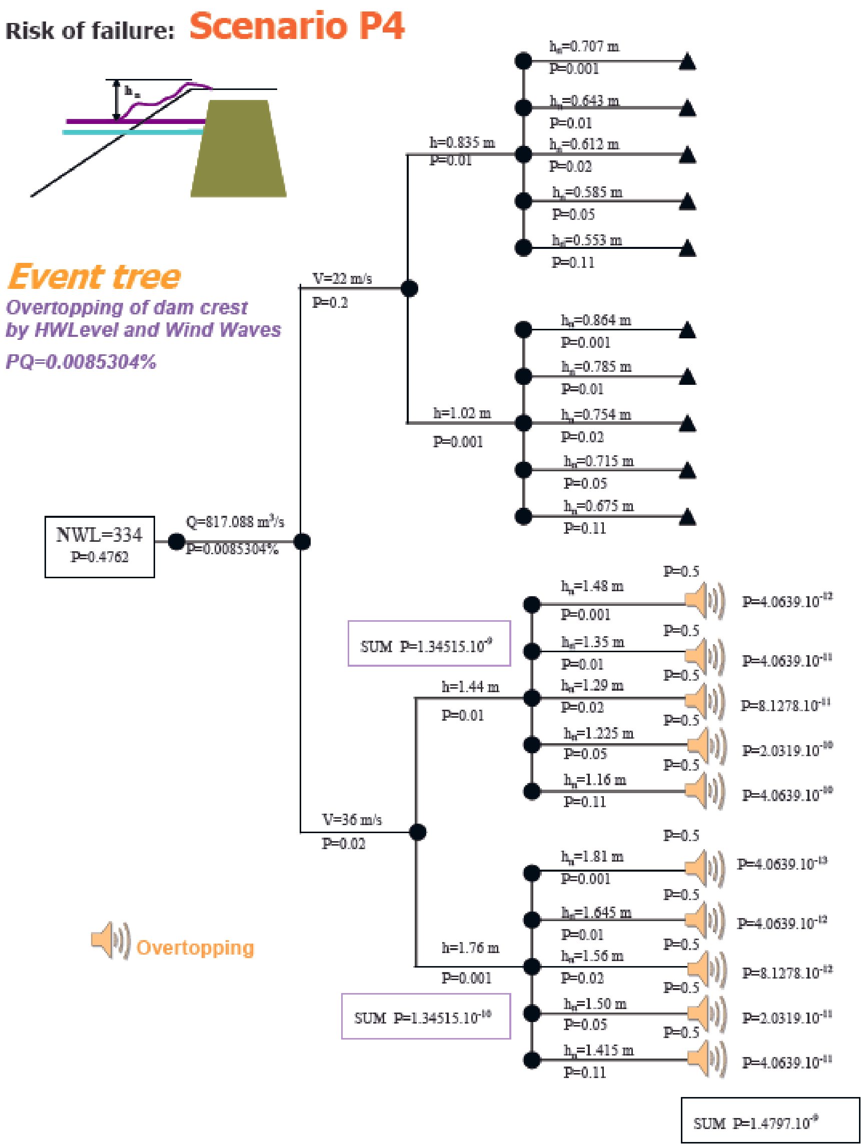


Figure 6. Event tree of the failure scenario P4 (see Table 2)

Basic conclusions of risk assessment are made by comparison between estimated risk levels and Bulgarian Safety Regulations where the recommended limits of probability interval are: P $\in$(3.10-5; 5.10-5). Then the limited results are (see Table 2):

- P1> =5.10-5
- P0< =5.10-5 & P0> =3.10-5

CONCLUSION AND FUTURE RECOMMENDATIONS

- The longer series for water level and discharges are necessary in the future.
- Other potential events for failure have to be included as earthquake, erosion, dam stability, gate damages, bottom outlet devices, etc.
- Having in mind the above mentioned points a comprehensive analysis is necessary on the basis of Decision Theory.
- The previous analysis of FIS shows that the Weibull distribution is the best way to model flood in small scale design area. Of course this result must be approved in the future. The authors hope they will be able to extend the results using a neuron-fuzzy procedure.

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