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THE PROBABILISTIC SOLUTION OF DIKE BREACHING DUE TO OVERTOPPING

TEZE DISERTAČNÍ PRÁCE – zkrácená verze
DOCTORAL THESIS – short version

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BRNO 2016

KLÍČOVÁ SLOVA

Analýza spolehlivosti; citlivostní analýza; Latin hypercube sampling; nejistota; odolnost vymílání; porušení hráze; přelití hráze.

KEYWORDS

Dike breaching; dike overtopping; Latin hypercube sampling; reliability analysis; scour resistance; sensitivity analysis; uncertainty.

MÍSTO ULOŽENÍ ORIGINÁLU DISERTAČNÍ PRÁCE

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1 INTRODUCTION

Constructing dikes or levees began at riversides to protect the urban areas against floods namely to protect people and property against the destructive effects of floods. Therefore, dikes are considered a vital part regarding to the modern flood risk management. Most countries have many dikes in their river and costal systems and it was estimated that there are several hundreds of thousands of kilometres of dikes in Europe and USA alone (Handbook 2013).

Potentially endangered areas cannot be absolutely protected against floods due to the fact that no dike design has 100 % reliability against the failure. Therefore, the dike reliability as a research issue is still important topic.

2 AIM OF THE WORK

The main goal of the thesis is to analyse the reliability of flood protection dike by estimating the probability of dike breaching due to overtopping. For this purpose, the method of qualitative and quantitative analysis is used. In terms of qualitative analysis, method of event tree analysis (ETA) was used, namely the possible incident scenarios during the progress of dike breaching due to overtopping (Fig. 1) were discussed. Then, the subsequent quantitative analysis of that event tree was used in order to achieve the probabilistic estimation of the dike breaching process involving its event scenarios. For the purpose of quantitative analysis, the Latin hypercube sampling (LHS) method was used as a statistical modelling method.

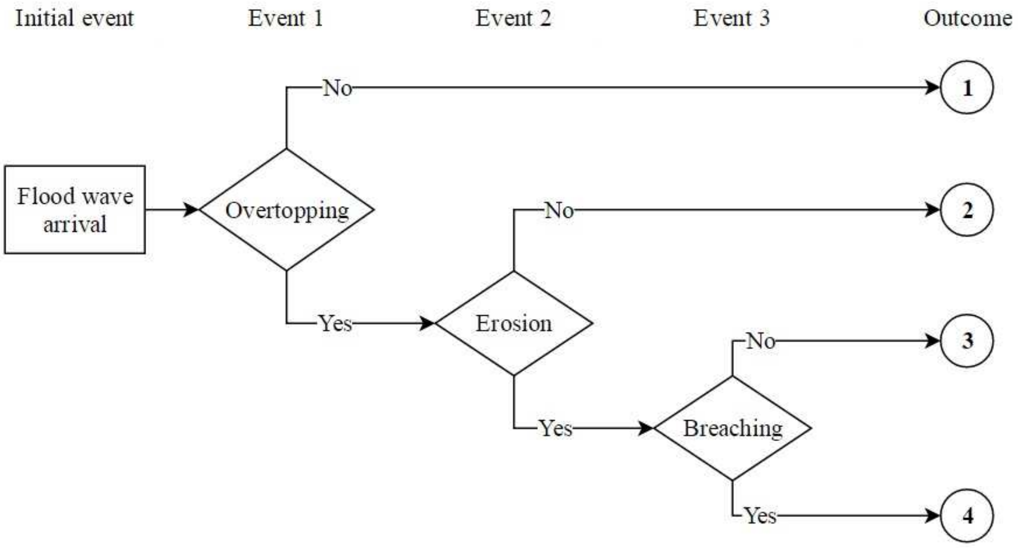

Fig. 1 Event tree for dike breaching due to overtopping

3 BASIC PARAMETERS OF DIKE BREACHING

The main parameters controlling the progress of dike breaching due to overtopping have been determined based on the gained experience from studying and analysing real previous events of dike and dam failure due to overtopping.

For the purposes of this work, the evolution over time of the dike breaching due to overtopping from the beginning of the flood wave until the complete collapse of the dike was clarified using the following parameters (Fig. 2) (Wahl 1998, Jandora and Říha 2008):

- Time of beginning of flood wave $t = 0$.
- Duration of flood wave arrival phase is the period during which water level gradually increases in the river and does not exceed the dike crest elevation (no overtopping).
- Time of beginning of overtopping t_o is the instant when water begins to overflow the crest.
- Duration of the resistance phase lasts from the instant of beginning of dike overtopping until the instant of beginning of dike erosion (overtopping – no erosion). Therefore, it represents the period during which the overflowing water on the dike crest and its downstream slope does not cause any erosion of the dike body. This period is attributed to the dike resistance caused by existence of the protective layer covering the dike crest and its downstream slope.
- Time of beginning of the dike erosion t_e is the instant when the load resulting from overflowing water on the dike crest and its downstream slope exceeds the dike resistance.
- Duration of breach initiation phase begins with the first erosion of the dike body on its crest or its downstream slope and ends with the instant of beginning of the dike breaching (erosion – no collapse). During this phase, a gradual backward erosion of the dike body initiates while the dike crest elevation remains constant.
- Time of beginning of the dike breaching t_b is the instant when the dike crest elevation decreases downward due to the backward erosion of the dike body. From this instant, there is a danger of the immediate dike failure. This danger usually initiates warning signals and the announcement of evacuation in the area downstream of the dike.
- Duration of breach formation phase is the period from the instant of beginning of the dike breaching until the end of the flood wave (collapse). During this phase, the maximum breach size and the maximum breach discharge are reached.
- Time of reaching the maximum breach discharge t_{max} is the instant when the maximum breach discharge Q_{bmax} flows through the breach opening. This t_{max} usually corresponds to the instant when the maximum breach size is attained.

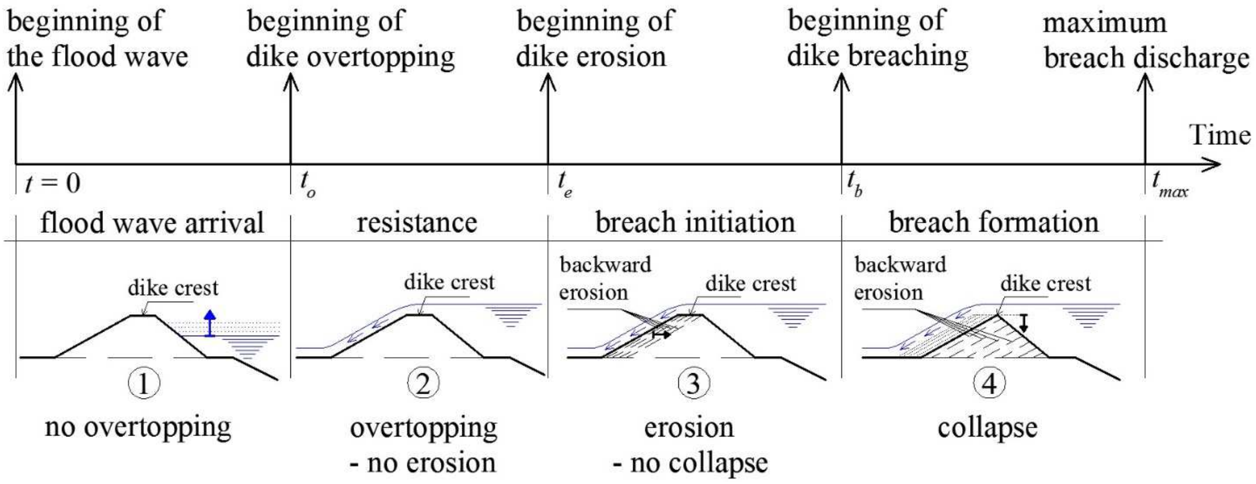

Fig. 2 Time related parameters of the dike breaching due to overtopping

4 MECHANISM OF DIKE BREACHING DUE TO OVERTOPPING

As mentioned before, the breach formation due to local erosion starts when the parameter of erosion load exceeds critical values specifying the resistance of the dike crest and its downstream slope against the surface erosion caused by the overflowing water. In the case of homogeneous dikes, shear stress and flow velocity are the most common parameters defining the erosion load. The critical shear stress and the non-scouring velocity are the corresponding parameters defining the resistance of dike material against the erosion process.

The comparison between the flow shear stress (erosion load) and the critical shear stress (resistance against erosion) as adopted analytical method for dam breach modelling ca be used (according to some authors' conclusions) only in the case of embankments without a cohesive core or in the case of dams built from homogeneous cohesive material (Jandora and Říha 2008). The same conclusion can be extended for the comparison between the flow velocity and the non-scouring velocity. In case of homogeneous dikes and with progression of breaching due to overtopping, the breach discharge increases outwards in the perpendicular direction to the dike's axis. During the gradual backward erosion of the dike body, slope of the downstream face remains approximately identical with the initial slope (Fig. 3).

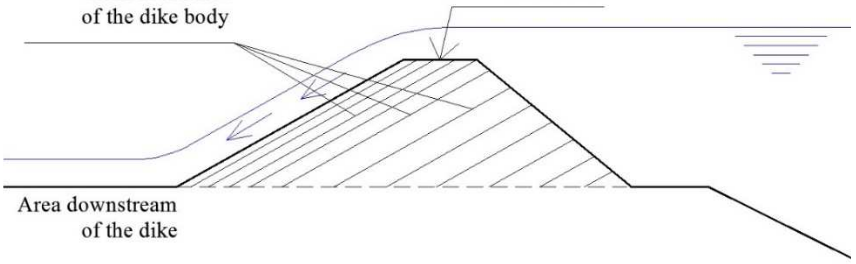

Fig. 3 Diagram of progress of a homogeneous sandy dike failure (Fread 1988)

5 Scour resistance of the dike surface

In case of dike surface protected by lining layer, several researches for estimating the scour resistance of the lining materials on steeper slopes were focused on surfaces protected by grass or granular materials. Numerous authors were carried out their experimental researches with physically modelled dam or dike in order to develop empirical relations defining the resistance of lining materials using the common variables of critical shear stress, non-scouring velocity, critical specific discharge or critical Froude number.

For assessing the resistance against erosion load for particular types of dike's protective lining layer using the non-scouring velocity (the limiting velocity according to Floods and reservoir safety 1996), the graphs presented in Fig. 4 were used in this thesis.

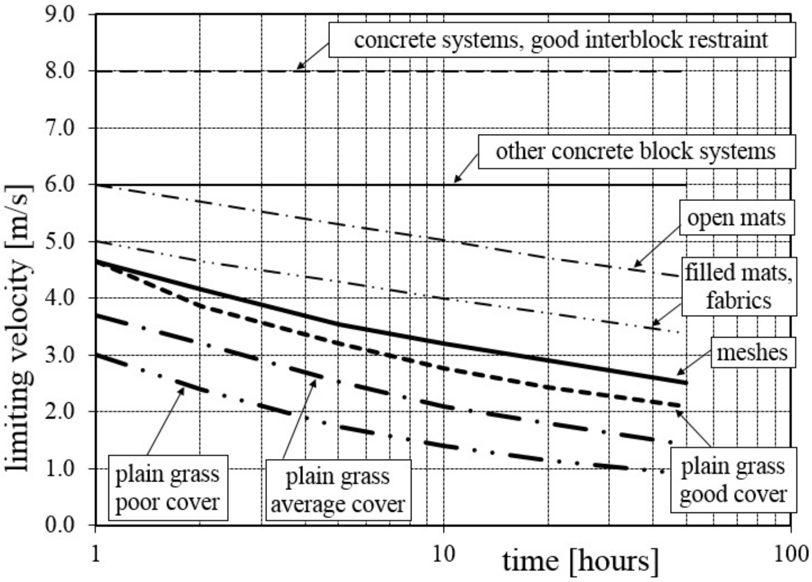

Fig. 4 Non-scouring velocity for selected types of surfaces as a function of overflowing time (Floods and reservoir safety 1996)

6 Conceptual approach

The main cause of dike breaching due to overtopping is the problem of surface erosion of the dike material induced by overflowing water on the dike crest and its downstream slope. Therefore, the dike breaching can be divided into two processes: the overtopping process (first stage) and the erosion process (second stage). Depending on more detailed analysis, the dike breaching process due to overtopping can be analysed and divided into its sequential events, allowing the following typical phases to be distinguished (Figures 2 and 5) (Singh 1996):

1. Flood wave arrival (no overtopping): during this phase, water level in the river gradually increases but does not exceed the dike crest elevation.
2. Resistance (overtopping - no erosion): the dike material and the protective layer on the downstream slope resists the overflow for some time. The resistance

mainly depends on the overflow velocity, the dike material and the protective layer on the downstream slope.

3. Breach initiation (erosion - no collapse): during this phase, gradual breach formation at the downstream slope and dike crest is initiated due to local erosion when the non-scouring velocity of the downstream slope material is exceeded. In this phase, a small portion of the dike material from the downstream slope and the dike crest will be eroded but the dike crest elevation dose not decrease.
4. Breach formation (dike collapse): this phase represents the breaching of the dike due to backward erosion of the upstream slope. Usually when the backward erosion reaches the upstream slope, a rapid increase in the discharge through the breach initiates, which causes more intensive erosion of the upstream slope. During this phase, it is noticeable that there is a significant lateral widening of the breach opening namely a considerable amount of the dike material is being flashed away. The elevation of the breach bottom may reach the terrain elevation of the area downstream of the dike, and the lateral widening continues until the end of the flood event.

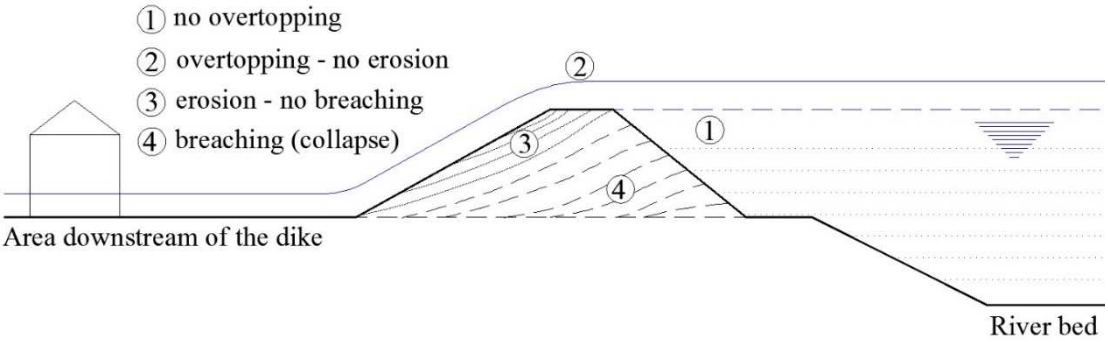

Fig. 5 Diagram of the failure of a dike due to overtopping

7 RELIABILITY ANALYSIS

Reliability as a general feature can be defined as the ability of a system to consistently perform its required function with maintaining the values of specified operational parameters within given limits according to specified technical conditions. The reliability quantifier is the probability of accomplishing the desired function. Basic procedures for reliability analysis are described below in this Chapter, see 7.1 and 7.2.

7.1 Qualitative analysis

The qualitative analysis is the first step of reliability analysis and aims to identify the weakest elements of the system and accordingly to identify the possible modes of the system failure. The first step of the qualitative analysis is defining the relationships connecting the elements of the evaluated system, their vulnerability and the possible consequences of their failure. This enables to build the various event scenarios that will be analysed by further methods such as the event tree analysis or the fault tree analysis. Those methods are verbal and largely dependent on the experience of the researcher.

In the qualitative analysis of any system we proceed as follows (Říha a kol. 2005):

1 Definition of the system.

2 Compilation of the checklists.

3 Compilation of diagrams of the system elements.

4 Compilation of the failure modes.

5 Analysis, for instance using Event Tree Analysis (ETA).

7.1.1 Checklists of the problem

A. Checklist of the problem of dike breaching due to overtopping includes the following elements.

B. Checklist of the event scenarios of this problem consists of the following typical phases described in Chapter 6:

1- First phase: Flood wave arrival (no overtopping).

2- Second phase: Resistance (overtopping – no erosion).

3- Third phase: Breach initiation (erosion – no collapse).

4- Fourth phase: Breach formation (dike collapse).

7.1.2 Event tree analysis (ETA)

Event tree analysis (ETA) is a logical modelling technique investigates the system responses through a single initial event in order to assess probabilities of the consequences (for both success and failure of the system) by analysing the total system (Clemens et al. 1998).

Objectives and results of the event tree analysis can be summarized as follows:

- Determining various possible event scenarios and the system conditions resulting from the initial events.
- Identifying the favourable condition of the system, which means that the elements of the system perform their functions (functional elements result in success of the system).
- Identifying the unfavourable condition of the system, which means that one of the elements is not functional and results in failure of the system.
- Classifying different modes of system failure according to event scenarios.
- Determining the probability of individual event scenario, which leads to the

favourable (success) or unfavourable (failure) condition of the system.

Event tree of the problem of dike breaching due to overtopping is plotted in Fig. 7 where the possible event scenarios are presented. Conditions, phases and related parameters of the problem of dike breaching due to overtopping are plotted in Fig. 6.

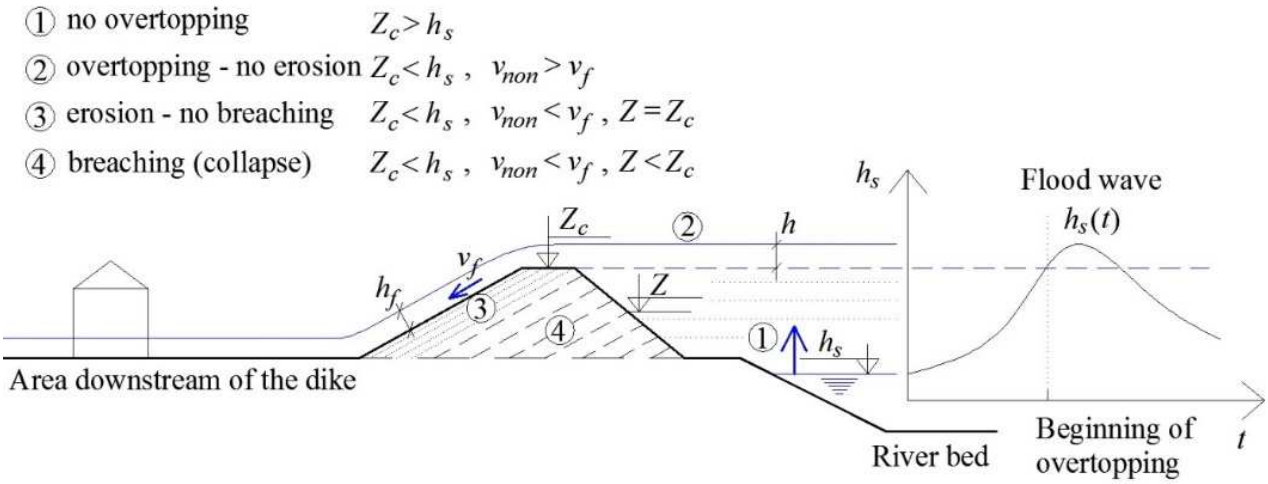

Fig. 6 Schematic diagram of the events during the process of dike breaching due to overtopping

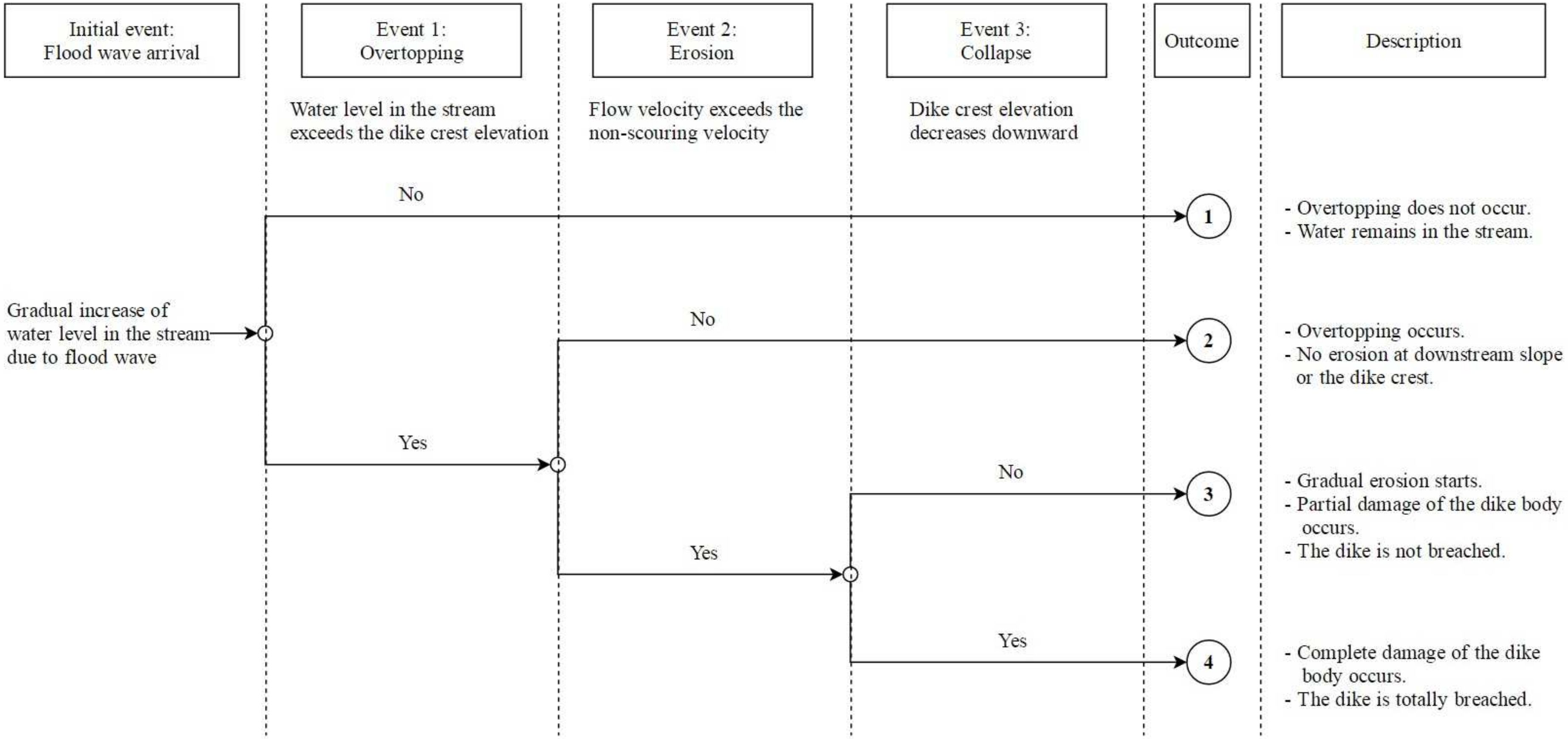

Fig. 7 Event tree of the process of dike breaching due to overtopping

7.2 Quantitative analysis

The main objective of the quantitative analysis within this thesis is to estimate the probability of each outcome obtained from individual event scenario. For this purpose, the probability of each event investigated using the ETA method (Fig. 7) will be firstly estimated and then the reliability of the entire system (the dike) will be estimated based on the probability of individual event scenario. For instance, the probability P_B of dike breaching due to overtopping will be estimated based on the probability P_F of arrival of the corresponding flood wave, the probability P_O of dike overtopping and the probability P_E of dike erosion (Fig. 8).

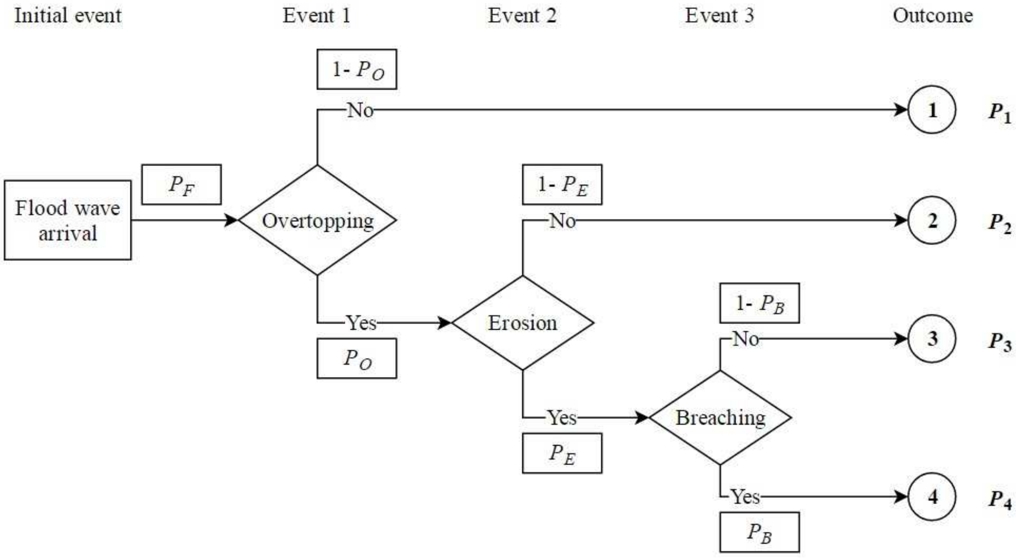

Fig. 8 Event tree for estimating the probability of dike breaching due to overtopping

7.3 Formulation of the problem

Failure (breaching) of the dike can be defined as the termination of the dike ability to perform its desired function when the value of one parameter (or several parameters) exceeds its critical value. Further, the consequent damage will be partial or complete.

Therefore, the dike reliability R can be defined as the probability that the dike strength S (or resistance) is equal to or larger than the load L applied to the dike (Fig. 9). This definition can be expressed as follows:

$$R = P(S \geq L) = P(S - L \geq 0) \tag{1}$$

Conversely, the dike failure F can be generally expressed as follows:

$$F = 1 - R = 1 - P(S \geq L) = P(S < L) \tag{2}$$

For the purpose of probabilistic solution, a sufficient number of simulations should be performed (Fig. 9). The quantities S and L will be considered random variables and their values will be randomly determined using a random sampling method (LHS) taking into consideration the probability distribution of each variable. Subsequently the probability P_i (Fig. 8) of each outcome obtained from individual event scenario investigated using the ETA method can be simply estimated by the frequency analysis as follows:

$$P_i = \frac{M_i}{N_{total}} \tag{3}$$

where M_i is the number of simulations realizing the outcome (i) (Fig. 8) and N_{total} is the total number of simulations.

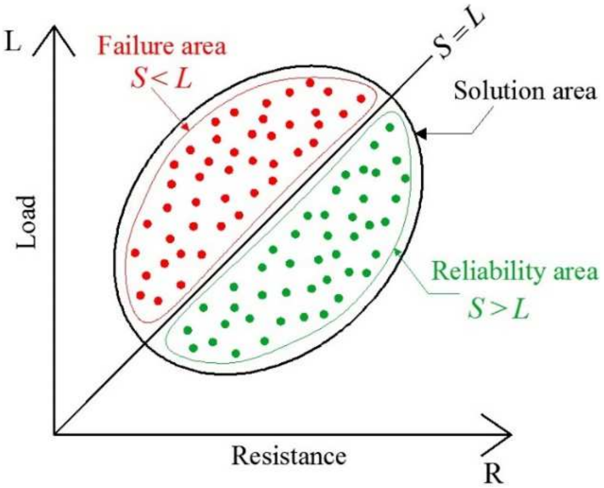

Fig. 9 Definition of reliability and failure of a dike according to equations 1, 2

8 Model of dike breaching

8.1 Conceptual model

The problem of dike breaching due to overtopping is a complex problem involving hydraulic and erosion transport phenomena. In this work, the following extensive simplifications were taken into account when proposing the mathematical model:

- Water flow along the downstream slope is approximated by quasi-steady flow (Singh 1996).
- The 3D process of dike breaching is approximated by a 1D model.
- The breaching starts at the lowest point of the dike crest where the first overtopping occurs.
- The overtopping width along the dike crest is suggested as an initial value (b_0) (Fig. 10). This value remains constant during the dike overtopping until the erosion starts.
- The resistance against surface erosion is evaluated with respect to the velocity of water flowing at the downstream slope. The limit cross-sectional velocity (Fig. 4) is used for this evaluation.
- Parallel gradual backward erosion of the downstream slope is assumed, as is

shown in the diagram in Fig. 3 (Fread 1988).

- The shape of the breach opening is approximated by a rectangle (Fig. 10). Dike erosion progress is in both the downward and lateral direction. During the erosion, the bottom of the breach opening remains horizontal and the sides remain vertical.

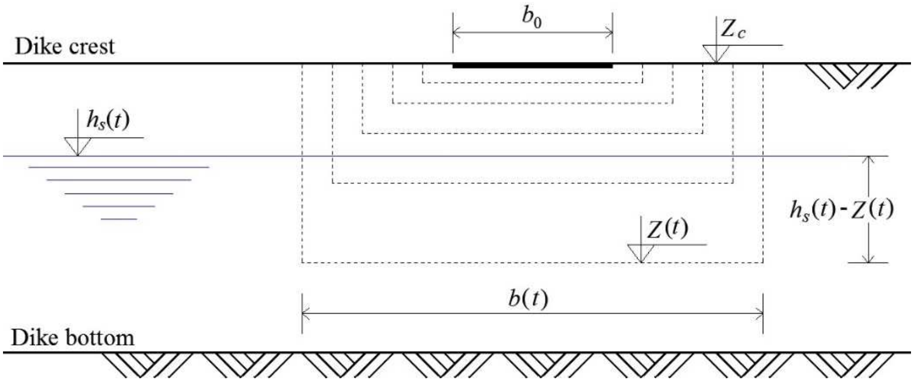

Fig. 10 Proposed section of the dike breach opening

8.2 Mathematical model

As mentioned before, the mathematical model characterizing the dike breaching process consists of two modules: the hydraulic module and erosion module.

A. The hydraulic module:

In order to describe water flow during dike overtopping the following state variables have been determined:

- $Q_b(t)$ flow discharge over the dike crest, or through the breach opening;
- $b(t)$ overtopping width before the erosion starts (equal to b_0) or breach opening width during the erosion process (determined by the erosion module);
- $h(t)$ overflow head;
- $v_f(t)$ mean cross-sectional flow velocity at the downstream slope;
- $h_f(t)$ water depth along the downstream slope.

Overflow head $h(t)$ is determined as the difference between the water level in the river $h_s(t)$ and the elevation of dike crest Z_c (or the elevation of breach opening bottom $Z(t)$ during the erosion process):

$$h = h_s - Z_c \tag{4}$$

where h_s is considered constant along the breach opening.

Water flow over the dike crest is given by the equation:

$$Q_b = m \cdot b \cdot \sqrt{2 \cdot g} \cdot h^{3/2} \tag{5}$$

where m is the discharge coefficient (for broad-crested weir), g is the acceleration of gravity.

The water depth h_f of the flow on the downstream slope can be derived from the Chezy formula with the assumption of uniform and quasi-steady flow:

$$h_f = \left(\frac{Q_b \cdot n}{b \cdot \sqrt{\sin\beta}} \right)^{6/10} \tag{6}$$

where β is the angle of the downstream slope, n is Manning's roughness coefficient.

Flow velocity v_f at the downstream slope is given by Chezy formula:

$$v_f = \frac{\sqrt{\sin\beta}}{n} \cdot h_f^{4/6} \tag{7}$$

The initial conditions for the overtopping problem - at time t_o (Fig. 2) - hold:

$$h(t = t_o) = h(t_o) = 0$$
$$b(t = t_o) = b(t_o) = b_0 \tag{8}$$

where b_0 is determined as the idealized initial width of the dike crest depression at the overtopping location.

B. Erosion module:

A simple 1D mathematical model was proposed for modelling the erosion process as it affects the dike body. Unknown variables in the erosion model are:

- $b(t)$ the breach opening width;
- $Z(t)$ the elevation of dike crest or the highest point of the breach opening bottom.

After exceeding the dike surface resistance ($v_f > v_{non}$), the elevation $Z(t)$ is determined by Equation 7.6 using the erosion module. Simple state equations can be used to calculate above mentioned variables (Singh 1996), (Jandora and Říha 2008):

$$\frac{dZ}{dt} = -\alpha_1 \cdot v_f \text{, for } v_f > v_{non} \tag{9}$$

$$\frac{db}{dt} = +\alpha_2 \cdot v_f \text{, for } v_f > v_{non} \tag{10}$$

where dZ/dt is the instantaneous change in the elevation of the breach opening bottom, db/dt is the instantaneous change in breach opening width, t is the time when $t > t_b$ (Fig. 2), α_1 and α_2 are empirical coefficients expressing the erodibility of the dike material. The value of α_1 can be determined by analysing real dam failure records (Jandora and Říha 2002, 2008), and the value of α_2 can be estimated within the interval $\left\langle \alpha_1/20; \alpha_1/5 \right\rangle$ (Singh 1996).

The initial conditions for the erosion problem hold:

$$b(t = t_b) = b(t_b) = b_0$$

$$Z(t = t_b) = Z(t_b) = Z_c \tag{11}$$

8.3 Schematization of the flood wave

In this study the flood hydrograph was approximated by a trapezoidal or triangular shape (Fig. 11). This approach is sufficiently variable to be able to describe the hydrographs of various flood waves. The approximated shape of the flood wave was schematically represented by the peak discharge Q_N and by three sections as follows (Fig. 11):

1- The ascending limb reflects the increase in the discharge due to the flood wave arrival. A linear increase in the discharge over time was assumed.

2- The horizontal limb approximates the duration of the peak discharge Q_N. Time interval t_d specifies the duration from when the peak discharge is reached until the beginning of the falling limb.

3- The descending limb represents the gradual decrease in the flood discharge. A linear decrease in the discharge over time was assumed and three times of t_k value was assigned for this time interval (Fig. 11).

The value of the peak discharge Q_N of the flood wave is provided by the Czech Hydro-meteorological Institute CHMI (in Czech: Český Hydrometeorologický Ústav ČHMÚ) for an N-year flood frequency for a given river profile in the Czech Re-public.

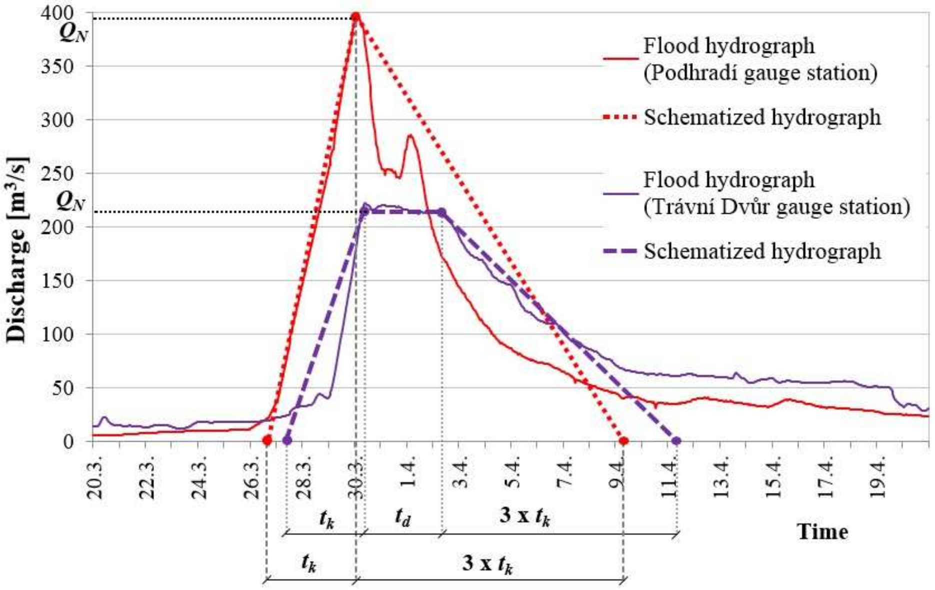

Fig. 11 Schematization of flood hydrograph at two gauge stations on the Dyje river

9 PROBABILITY OF DIKE BREACHING DUE TO OVERTOPPING

9.1 Uncertainty in input parameters

From the point of view of uncertainty, each input parameter is a variable and ranges within an interval <min; max> of values which are supposed to be realistic in practical situations. Therefore, all input parameters should be individually identified and their impact on the results of the solution must be analysed.

The uncertainty in the input parameters of the dike breaching model was taken into account in order to obtain a probabilistic solution for the problem. The relevant parameters were classified into three groups:

1. Parameters describing the flood wave: Q_N, t_k, t_d (Fig. 11).
2. Parameters of the hydraulic module: b_0, m, n (Equations 8, 5, 6).
3. Parameters of the erosion module: v_{non}, α_1, α_2 (Equations 9, 10).

9.2 Sensitivity analysis

The sensitivity analysis aims for revealing the influence of change in the value of each input parameter on the values of output parameters. The response of a mathematical model to changes in the input parameters is important in order to evaluate the model applicability and to define the input parameters that considerably affect the output parameters and thus deserve an additional attention.

In the case of dike breaching problem, the maximum breach discharge, the volume of water flowed through the breach, the breach opening size and the duration from the beginning of dike overtopping until the dike failure can be considered the most significant output parameters.

The influence of the input parameters mentioned above (in subsection 9.1) on the outputs of the dike breaching problem was taken into consideration when selecting parameters for random sampling. In this study the screening method was used to identify the non-influential input parameters. The most-used screening method in engineering is based on the so-called “One-At-a-Time” OAT design, where each input is varied while keeping the others constant (Iooss and Lemaitre 2014).

9.3 Estimation of the probability of dike breaching

The assessment of the probability was related to the typical phases of the dike breaching process specified in Fig. 5.

For the purpose of the probabilistic solution, a random sampling procedure was used where a set of simulations of dike breaching due to overtopping was generated with the consideration that the value of each uncertain input parameter changes within an interval of values with a specific probability distribution.

Using the Latin Hypercube Sampling (LHS) procedure, the sets of input parameters’ values were randomly sampled and applied in the deterministic model to generate a set of output parameters.

The probability P_i of each typical i-th phase of the dike breach was estimated by frequency analysis as follows:

$$P_i = \frac{\text{number of simulations realizing the phase } (i)}{\text{total number of simulations}} \tag{12}$$

9.4 Latin hypercube sampling (LHS) method

The Latin hypercube sampling (LHS) method is an extension of quota sampling (Steinberg 1963) and can be viewed as an *n*-dimensional generalization of Latin square sampling (Raj 1968). The procedure of generating samples using LHS method can be summarized as follows:

- When sampling a problem with K input parameters, the range of probable values of each input parameter should be divided into a number of intervals (J) of the same probability (Fig. 12). The number of intervals J depends on how many samples (values) would be generated for the input parameter.
- Then, one value from each interval is randomly selected with respect to the probability density in the interval.
- In case that all input parameters have the same J, the entire probability space consisting of K input parameters is divided into J^K cells of the same probability and thus number of the possible combinations of inputs' values according to LHS technique is equal to J^K.
- The combination or cell index indicates the intervals index of the input parameters. For example, the cell index (2, 1, 3) shows that the generated pseudo-random values of three input parameters ($K = 3$) respectively lie in the 2nd interval of the 1st parameter, in the 1st interval of the 2nd parameter and in the 3rd interval of the 3rd parameter.
- For each selected (generated) combination of pseudo-random values, the deterministic calculation according Fig. 7 was carried out. The result of such calculation corresponds to one of the event scenarios (Fig. 8) and hence was applied to equation (3).

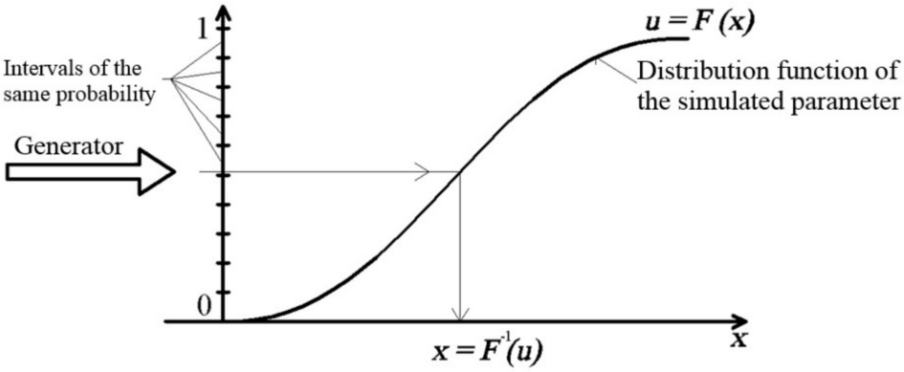

Fig. 12 Generating random values of an input parameter with intervals $J = 10$

10 Case study

10.1 Description of the studied dike

The studied dike is located on the left bank of the Dyje River at the stationing about 28.8 km. This location is adjacent to the village of Ladná near the town of Břeclav in the Czech Republic (Fig. 13). A diagram of the dike's cross section and geometrical dimensions is shown in Fig. 14. The location of the potential overtopping and subsequent breaching was selected during the site investigation at the lowest point on the dike crest.

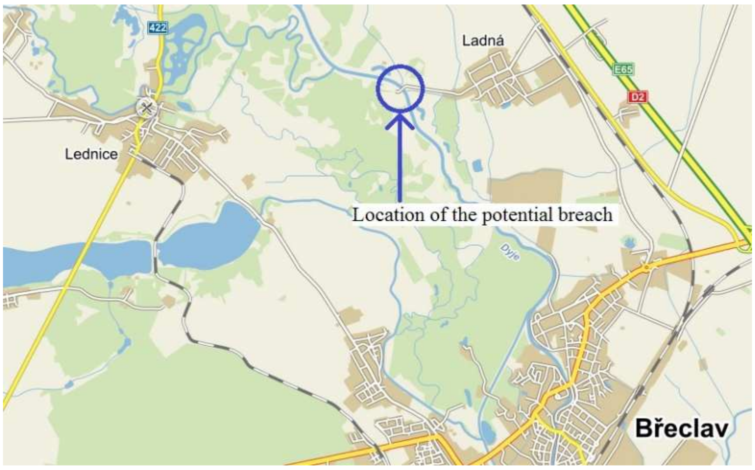

Fig. 13 Location of the potential breach at the Dyje river

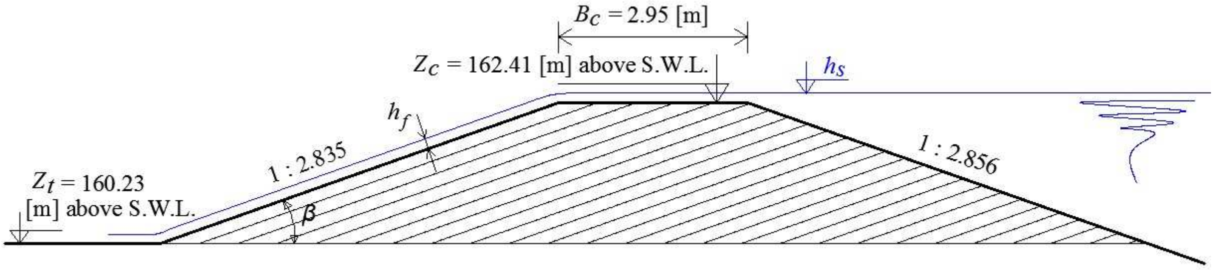

Fig. 14 Dike cross-section at the location of potential breach

10.2 Definition of the flood wave

The parameters of the flood hydrograph were set up for the chosen locality mentioned before as follows:

1 Values of peak discharge Q_N provided by ČHMÚ are summarized in Table 1.

Table 1 Values of N and Q_N (provided by the ČHMÚ)

N [year]	1	2	5	10	20
Q_N [m^3/s]	160	230.9	341.4	436.4	540.8
N [year]	50	100	500	1000	10000
Q_N [m^3/s]	693.3	820	1154.8	1320	1920

2 The duration of the ascending limb was derived from the floods in summer 2002, spring 2006 and summer 2006 along the Dyje River; t_k was considered to range within the interval <48; 120> [hour].

3 The duration of the horizontal limb t_d was assumed to range from 0 hours (the rising limb is immediately followed by the falling limb - triangular shape) to 120 hours based on data obtained from past flood events.

4 The duration of the descending limb was determined based on typical observed hydrograph shapes of past flood events to be $3.t_k$.

10.3 Sensitivity analysis

In the sensitivity analysis the influence of input parameters Q_N, t_k, t_d, b_0, m, n, v_{non}, α_1, α_2 on the output variable Q_{bmax} was assessed. In the analysis non-dimensional parameters of the inputs and the output were compared. Firstly, a reference value (R_i) was specified for each input parameter and processed to form the following serial values $\mathbf{V}_i = [0.7R_i, 0.8R_i, 0.9R_i, R_i, 1.1R_i, 1.2R_i, 1.3R_i]$. During the analysis each input parameter is substituted by its serial values while keeping the others constant equal to their R_i values. The Q_{bmax} value corresponding to each serial value for each input parameter was computed and used as a criterion in the sensitivity analysis. The procedure of sensitivity analysis for all input parameters was carried out via MATLAB software.

The resulting graph of the sensitivity analysis expressing the relation between the dimensionless input parameters ($\mathbf{V}_i$ / R_i) and the dimensionless maximum breach discharge ($Q_{bmax}(\mathbf{V}_i)$ / $Q_{bmax}(R_i)$) can be seen in Fig. 15 (values of input and output parameters used for creating Fig. 15 are summarized in Appendix A). The following conclusions can be stated:

- Parameters Q_N, t_k, t_d, m, n and α_2 are the most influential. Q_N has the highest influence on the output variable Q_{bmax}. t_k, t_d, m and α_2 have lower influence than Q_N, and n has reverse influence.
- Parameter v_{non} has only minor influence and parameters b_0 and α_1 have practically no effect on the output variable Q_{bmax}.

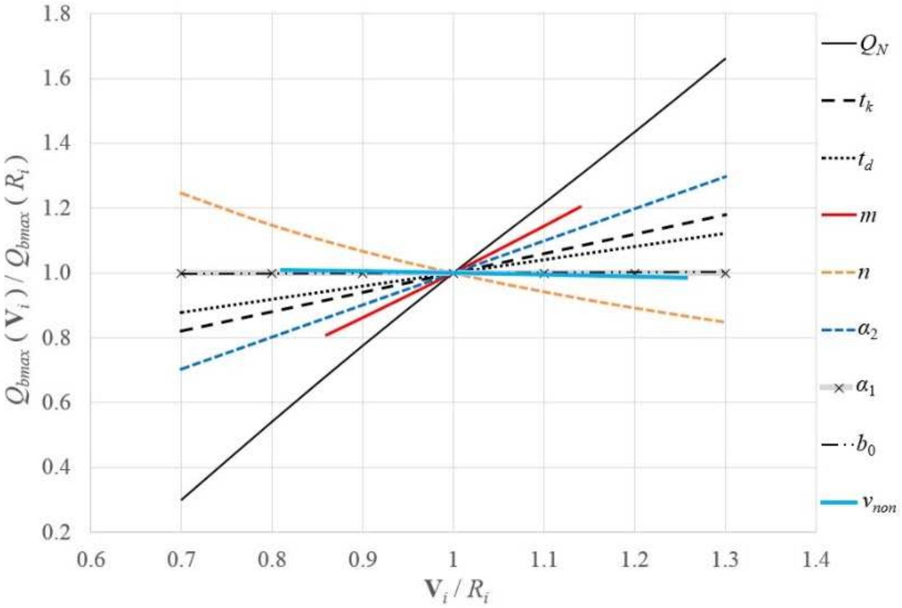

Fig. 15 Sensitivity analysis results

10.4 Detailed computational algorithm

The dike breaching computation is a dynamic process in which the breach discharge depends on the breach opening size (the elevation of the breach opening bottom $Z(t)$ and the breach opening width $b(t)$). The development of the breach opening depends on the capacity of flowing water to scour dike material during the breach, i.e. it depends on the flow velocity. The estimated change in the breach opening size parameters (ΔZ and Δb) due to the erosion process are used as initial inputs for the iteration in each time step.

The computational algorithm consists of the following steps (These following steps were carried out via MATLAB software:

1. Definition of the probability exceedance line (P, Q_N) (Fig. 16) to estimate the probability P of the peak discharge Q_N. This was done using the data provided by the ČHMÚ (Table 1) with the use of Equations 13 and 14:

   $$p_N = 1 - e^{-1/N} \tag{13}$$

   $$P = 1 - p_N = e^{-1/N} \tag{14}$$

   where Q_N is the peak discharge in a specific profile that can be reached or exceeded once every N year, P is the probability that the Q_N will not be reached and p_N is the probability that the Q_N will be reached or exceeded and the p_N values were calculated using the probability density function of the Poisson distribution with parameter $\lambda=1/N$.

   The fitting curve expressing the (P, Q_N) relation (Fig. 16) was defined via MATLAB software using N and Q_N values summarized in Table 1 and P values obtained from Equations 13 and 14.

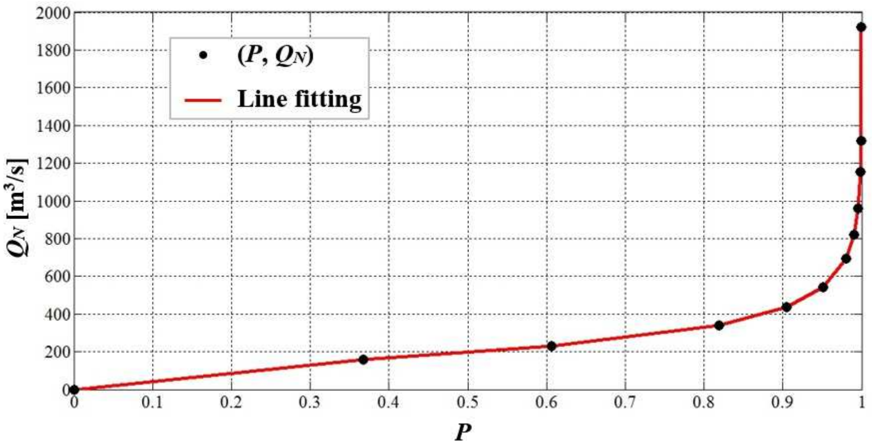

Fig. 16 Fitting curve expressing the (P, Q_N) created via MATLAB software

   Using the fitting curve (P, Q_N), the random values of the variable (Q_N) were obtained. The input parameters t_k, t_d, m, n and α_2 were also considered random variables. As there were no reliable data enabling the analysis of their probability density function, in this study their probability distribution was set to be uniform (see below).

2. Defining the flood wave parameters: The peak discharge and flood duration should be determined in order to obtain the hydrograph (Q, t) of the flood wave. The flood wave parameters plotted in Fig. 17 are as follows:

- Q_N is a value randomly chosen from the fitting curve using the LHS method (Fig. 16).
- t_k is a value randomly chosen using the LHS method from the interval <48; 120> hours with uniform distribution.
- t_d is a value randomly chosen using the LHS method from the interval <0; 120> hours with uniform distribution.

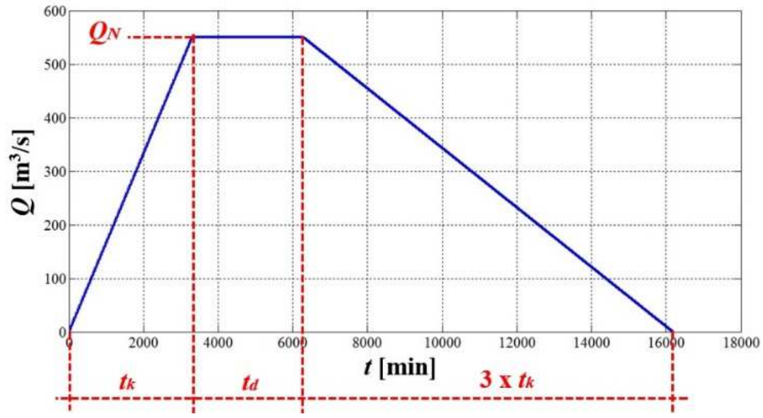

Fig. 17 Trapezoidal flood wave hydrograph (Q, t) created via MATLAB software

3. Defining the evolution of the water level in the stream (h_s, t) (Fig. 18). The water level in the stream (the Dyje River) is determined from the instant discharge in the river by the use of the stage-discharge curve (h_s, Q) at the Břeclav-Ladná gauging station.

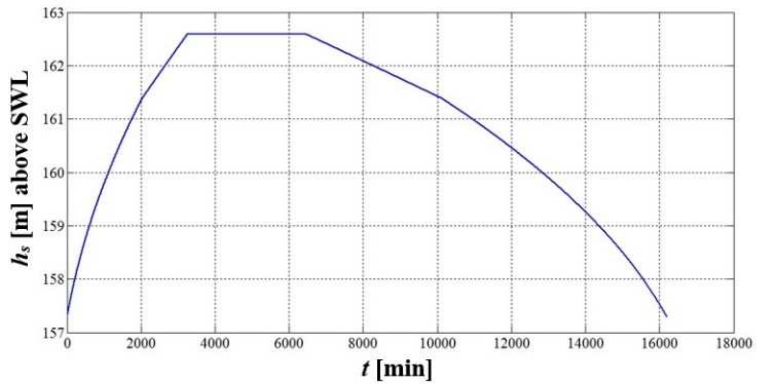

Fig. 18 Water level in the river (h_s, t) created via MATLAB software corresponding to trapezoidal hydrograph (Fig. 17)

Defining the dike crest elevation (Z_c). In this thesis, two different cases of the parametric study regarding the dike crest elevation and the protective lining layer were carried out:

- **<u>Case 1:</u>** The dike crest elevation Z_c was specified to be equal to the stream water level corresponding to the peak discharges with the return periods N = 10, 20 and 50 years, i.e. $Z_c = h_s$ (Q_{10}, Q_{20} and Q_{50}, respectively). In this case the dike crest elevation was specified for three different design discharge values in the Dyje River (Q_{10}, Q_{20} and Q_{50}) and this enables the parametric assessment of the probabilities related to different flood protection levels.

- **<u>Case 2:</u>** The dike crest elevation Z_c was specified to be equal to the stream water level corresponding to the peak discharge with the return period $N = 10$ years (one design discharge value) i.e. $Z_c = h_s (Q_{10})$. The lining layer covered the downstream slope of the dike was tested for all selected types of the lining materials presented in Fig. 4. This enables the parametric assessment of the probabilities related to different materials of the lining layer for one flood protection level.

4. Testing whether the water level in the stream h_s exceeds the dike crest elevation Z_c. If $h_s > Z_c$ (at time $t > t_o$ as shown in Fig. 2), calculation by the hydraulic module was performed using Equations 8.9 - 8.12. During the calculation, the random variables m and n (Equations 8.10, 8.11) were determined using the LHS method, where m values were randomly chosen from the interval <0.3; 0.4> and n values were randomly chosen from the interval <0.025; 0.045>, both with uniform distribution. Other parameters used in the hydraulic module were determined as follows: $b_0 = 2$ [m], $g = 9.81$ [m/s^2] and $\beta = 19.43$ [degree].
5. Testing whether flow velocity at the downstream slope v_f exceeds the non-scouring velocity v_{non}. If $v_f > v_{non}$, calculation of the erosion module was performed, where the instantaneous changes in the breach opening bottom elevation and overtopping width (breach opening width) were calculated using Equations 8.13, 8.14. α_1 was used as a constant ($\alpha_1 = 0.0005$), and the α_2 value was randomly chosen using the LHS method from the interval $<\alpha_1/20; \alpha_1/5> = <0.000025; 0.0001>$ with a uniform distribution.
6. If the elevation of the breach opening bottom reaches the elevation of the terrain behind the dike, and still $v_f > v_{non}$, only the breach opening width increases.
7. The procedure described in points 5 and 7 is repeated until the water level in the stream decreases together with the breaching velocity and erosion stops. The dimensions of the breach opening do not change from this time onwards.
8. Calculating the probability of each typical phase of the dike breaching due to overtopping described in Chapter 9 (see 9.3) was statistically carried out using Equation 12 and depending on the event scenarios described in Fig. 8, where:
   - P_1 corresponds the 1st phase (no overtopping),
   - P_2 corresponds the 2nd phase (overtopping – no erosion),
   - P_3 corresponds the 3rd phase (erosion – no collapse),
   - P_4 corresponds the 4th phase (dike collapse).

   For the purpose of random sampling and generating the combinations of input parameters' values 50 values for Q_N (those values were randomly chosen from the (P, Q_N) curve presented in Fig. 16 and specified to be larger than the design discharge value (Q_{10}) used for each case mentioned in step 4) and 10 values for each t_k, t_d, m, n and α_2 were randomly chosen. Therefore, 5.10^6 simulations (the possible combinations according to LHS technique is equal to $J^K = 10^{\wedge 5}.\ 50 = 5.10^6$) were carried out for each case mentioned in step 4.

11 FINAL RESULTS

The input data for the statistical modelling were as follows:

- Return periods N and the corresponding peak discharges Q_N.
- Initial breach opening width b_0 and α_1 were proposed as deterministic parameters.
- Parameters t_k, t_d, m, n and α_2 were specified with taking into consideration their uncertainty during the calculation. Their values were randomly chosen using the LHS technique and the uniform distribution of the values was suggested (Table 2).

Table 2 parameters of uniform distribution $U(a, b)$

Variable	Type of distribution	a	b
t_k	$U(a, b)$	48	120
t_d	$U(a, b)$	0	120
m	$U(a, b)$	0.3	0.4
n	$U(a, b)$	0.025	0.045
α_2	$U(a, b)$	0.000025	0.0001

The final results were performed for two cases as mentioned above (see 10.4, step 3):

- **Case 1:** The dike crest elevation was specified to be equal to three different values ($Z_c = h_s$ (Q_{10}, Q_{20} and Q_{50}, respectively) (Table 3), and the downstream slope of the dike is covered with plain grass – poor cover.
- **Case 2:** The dike crest elevation is equal to $Z_c = h_s(Q_{10})$, and the lining layer of the downstream slope was tested for all materials presented in Fig. 4 (Table 4).

The final results were presented as probabilities related to the annual occurrence of a given phase of the breaching problem. The results were presented in Figures 19 and 20 in the form of bar graphs of the typical phases with the probability values in percentage.

Case 1 results:

Table 3 Probabilities of the typical phases and comparison with the value obtained from equation 13

	p_n (equation 13)	No overtopping	Overtopping – no erosion	Erosion – no breaching	Collapse
$Z_c = h_s(Q_{10})$	0.90484	0.90595	0.00378	0.00003	0.09024
$Z_c = h_s(Q_{20})$	0.95123	0.95688	0.00198	0.00002	0.04112
$Z_c = h_s(Q_{50})$	0.98020	0.98543	0.00189	0.00001	0.01267

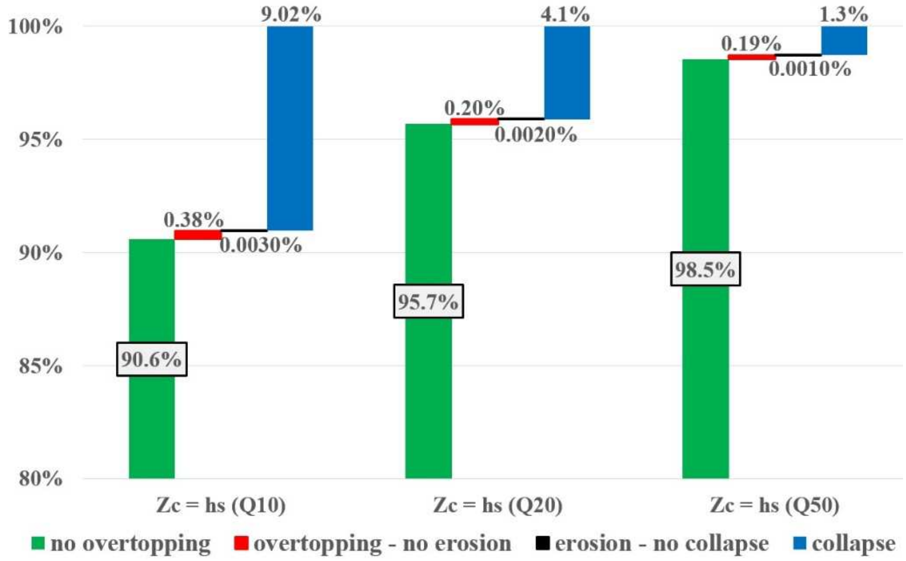

Fig. 19a Probabilities [%] of the typical phases of dike breaching due to overtopping

The next figure includes the same probabilities presented in Fig. 19a but in different probability scale.

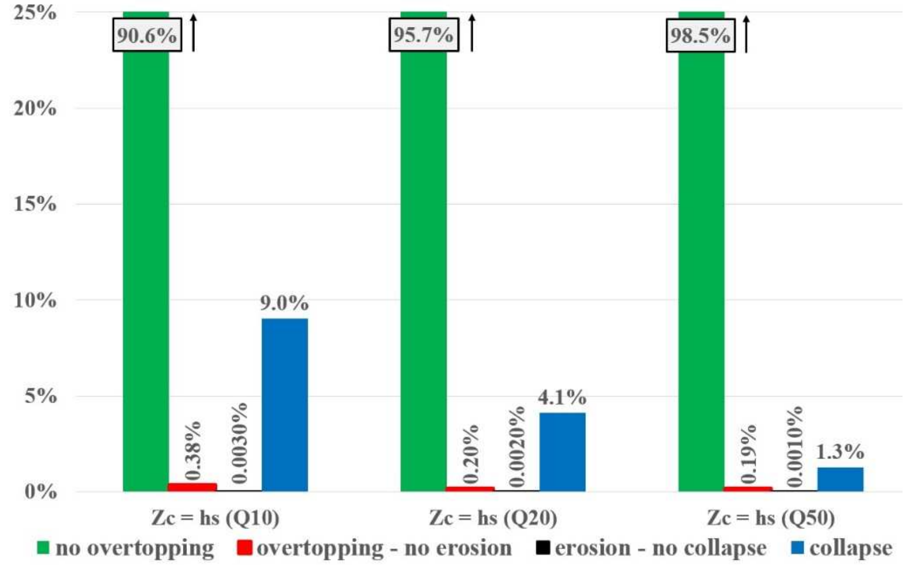

Fig. 19b Probabilities [%] of the typical phases of dike breaching due to overtopping

Case 2 results:

Table 4 Probabilities of the typical phases for different lining materials and comparison with the value obtained from equation 13

	p_n (equation 13)	No overtopping	Overtopping – no erosion	Erosion – no breaching	Collapse
A: grass poor cover	0.90484	0.90595	0.00377	0.00003	0.09024
B: grass average cover	0.90484	0.90595	0.00862	0.00003	0.08541
C: grass good cover	0.90484	0.90595	0.01505	0.00002	0.07897
D: meshes	0.90484	0.90595	0.01976	0.00002	0.07427
E: filled mats, fabrics	0.90484	0.90595	0.02993	0.00001	0.06411
F: open mats	0.90484	0.90595	0.04119	0.00001	0.05285
G: concrete block systems	0.90484	0.90595	0.07789	0.00000	0.01616
H: concrete systems	0.90484	0.90595	0.08974	0.00000	0.00431

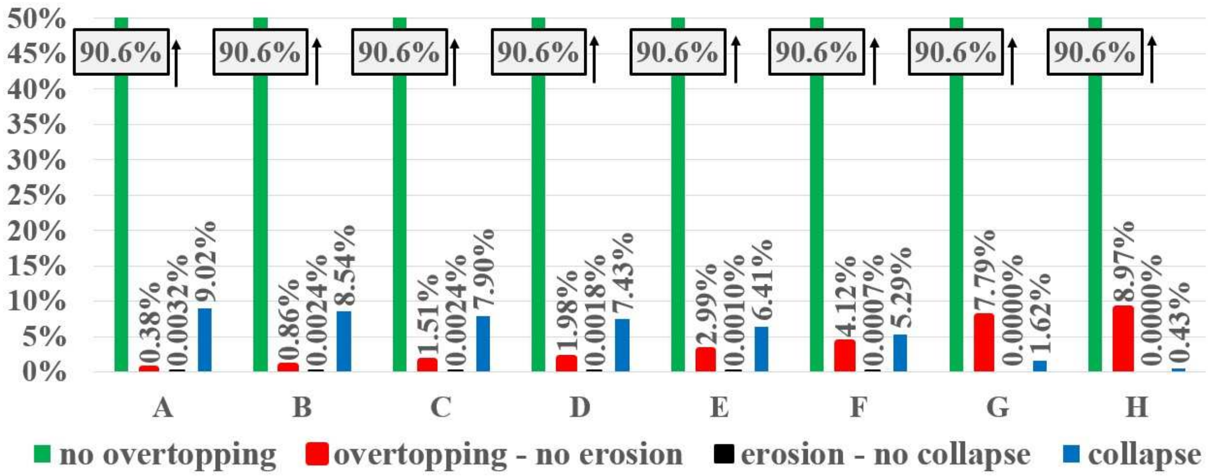

Fig. 20a Probabilities [%] of the typical phases for different lining materials

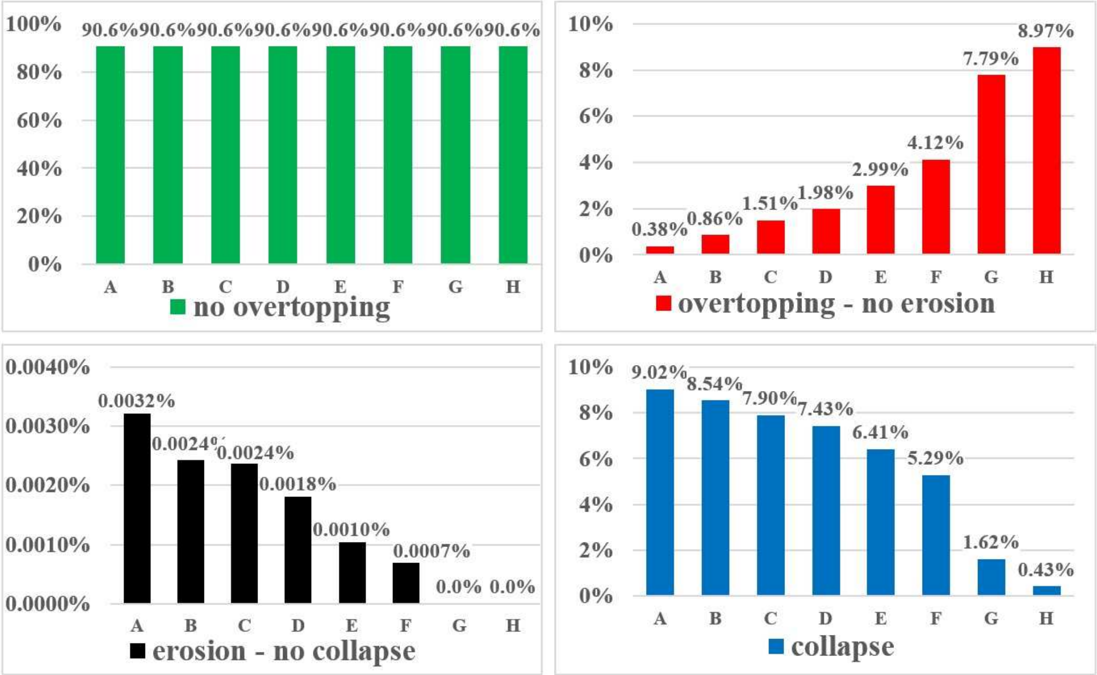

Fig. 20b Detailed Probabilities [%] of individual typical phases for different lining materials

12 CONCLUSIONS

The results for the "no overtopping" phase are in good agreement with the "accurate" results obtained from Equation 13 (see Tables 3 and 4).

The results presented in Figures 20a and 20b show that the probability of "dike collapse" decreases with the increase of resistance of the lining material. In Figures 19a, b and 20a, b the small values gained for the probability of "dike erosion - no collapse" phase, which represents the case of partial damage in the dike body without complete failure, can be attributed to the very long duration of the flood waves in the Dyje River simulated in this work.

During this thesis, numerous specific practical and theoretical problems were solved. These can be solved in more detail during further research:

- Comprehensive sensitivity analysis including more output variables should be carried out to study the influence of erodibility parameters on the breaching process in more detail.
- Due to the large number of simulations, the computing time needed for this study was extensive. It is therefore necessary to search for more efficient sampling methods (importance sampling, etc.). This will open up the possibility of using more complex dike breach simulation techniques, including 2D models.
- An initiative to compile a database of dike failures, dike materials, resistances of individual lining materials, etc. which should provide information for the development of more reliable probability distributions.

Finally, it can be concluded that this study indicates the ability to perform the probabilistic assessment of dike failures. In practical cases, it can be applied to identify the most vulnerable reaches of dikes and to propose improvements to be made to these dikes at such reaches by installing more resistant linings or designing emergency spillways for the dikes.

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ABSTRACT

Doctoral thesis deals with reliability analysis of flood protection dikes by estimating the probability of dike failure. This study based on theoretical knowledge, experimental and statistical researches, mathematical models and field survey extends present knowledge concerning with reliability analysis of dikes vulnerable to the problem of breaching due to overtopping. This study contains the results of probabilistic solution of breaching of a left bank dike of the River Dyje at a location adjacent to the village of Ladná near the town of Břeclav in the Czech Republic. Within thin work, a mathematical model describing the overtopping and erosion processes was proposed. The dike overtopping is simulated using simple surface hydraulics equations. For modelling the dike erosion which commences with the exceedance of erosion resistance of the dike surface, simple transport equations were used with erosion parameters calibrated depending on data from past real embankment failures. In the context of analysis of the model, uncertainty in input parameters was determined and subsequently the sensitivity analysis was carried out using the screening method. In order to achieve the probabilistic solution, selected input parameters were considered random variables with different probability distributions. For generating the sets of random values for the selected input variables, the Latin Hypercube Sampling (LHS) method was used. Concerning with the process of dike breaching due to overtopping, four typical phases were distinguished. The final results of this study take the form of probabilities for those typical dike breach phases.