STATISTICAL EVALUATION OF HISTORICAL DIKE FAILURE MECHANISM

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ABSTRACT. - S**tatistical evaluation of historical dike failure mechanism** The failure mechanism of flood protection dikes includes physical (geotechnical, seepage) processes leading to a dike breach. An awareness of the failure mechanism is required directly in dike stability calculations and indirectly for risk calculations. Statistics of historical data indicate among others the distribution and frequency of failure mechanisms associated with dikes. These data may be used in estimations of the expected likelihood of occurrence of non-quantifiable failure mechanisms. In addition to a comparative evaluation of statistics collected in several countries, this publication also presents data for the Carpathian Basin. One of the most important conclusions drawn from statistical information suggests that most dike breaches develop as a consequence of poor safety strategy.

Keywords*:* flood protection dykes, dyke breaches, failure mechanism

1. Introduction

The literature on the failure mechanism of flood protection dikes is growing dynamically and covers a set of topics which are indispensable for determining dike failure probabilities but not primarily in terms of quantifiable failure mechanisms. Failure mechanism underpins the estimation of dike failure probability and reliability calculations.

Put simply, hazard is calculated as follows: after an initial survey of threats failure mechanisms need to be defined and used to estimate failure probabilities. Hazard can be calculated from failure probability and the quantification of dike failure consequences. Accordingly, to perform hazard analysis, it is necessary to know the probability of dike failure, and the first step in the process involves listing **potential** failure mechanisms.

2. Dike failure causes

Failure mechanism is frequently confused with other concepts, such as the reason for dike breach, or human errors, or natural process and events giving rise to

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a dike failure. When studying the process of a dike breach developing, we look for reasons that have triggered the failure. These reasons may be classified into two large groups:

- existing properties, and
- direct causes of failure.

Existing properties include, for instance, inappropriately compacted earthworks, poor quality of embankment materials, poor safety concept, lack of access (Nagy 2009, 2010) to sites exposed to flood action to take countermeasures, ignoring the consequences of an earthquake, etc.

Direct causes of failure normally involve additional impacts at play immediately before a breach, reducing resistance levels, such as the weakening of the protected side of the dike, high water level, seasonal lack of wave protection, earthquake, etc.

Many also list information pertaining to the origin of a flood (ice jam, tsunami, heavy rainfall, etc.) among the causes of dike failures. These expressions should not be confused with the mechanism of dike failures, which is an engineering term and as such presents the processes giving rise to dike failure.

Failure always means dike breach. One has to distinguish phenomena that do not lead to dike failure and only take the form of dike damage[1]. Damage formation is also associated with mechanisms, which may be similar or identical to failure mechanisms, but damages are wider in scope as certain impairment mechanisms do not directly trigger dike breaches. We have no experience with subsequent dike failure following certain impairment mechanisms (such as slope dishing, water side slippage or hogging), although we actually have information of several phenomena of this kind. These occurrences are mostly possible to rectify and dykes can be restored before a subsequent surge of flood.

3. Methods for estimating probability of failure

Flood protection dykes are long (e.g. 4200 km in Hungary) eath structures with a relatively small cross section. When studying the stability of engineering structures of this kind, the first thing to do is section off the dyke lengthwise according to certain characteristics. Dividing dykes this way provides sections of identical behaviour represented by design cross sections. The probability of failure must be calculated for these design cross sections.

The probability of failure of a section of a flood protection dyke (Nagy 1996) can be calculated from the failure probability derived from failure mechanisms. To start with, therefore, one must calculate the probability of each failure mechanism associated with a cross section primarily by means of geotechnical methods. As various failure mechanisms can be defined (estimated)

[1] One must remark that damage may also deteriorate and develop into a failure.

using geotechnical and stability calculation methods - the calculations provide results in the form of cross section probabilities. Each section of a shorter or longer flood protection dyke (or the full flood defence system) can be associated with a failure probability value, which forms the basis of further calculations. That way it is easy to calculate the failure probability of a flood protection dyke or a flood area and investment budgets can be used in a more targeted and efficient manner.

The simplest method of defining the critical failure mechanism is as follows:

- The first step involves defining probable failure mechanisms.
- Probable failure mechanisms are then used to analyse the circumstances (site, reason, etc.) of actual failures. Next, the number of failure mechanisms need to be narrowed down to the ones that actually have the likelihood occur.
- Likely failure mechanisms are then used to define the critical failure mechanism. With that available one can estimate the most probable failure mechanism.
- There are certain erroneous activities that emanate from certain parts of the system and the errors and omissions of people working in the system. A probability of occurrence must also be quantified for each of these events.
- A failure mechanism may also take the form of a series of events. One can construct series of events tracing disorders and extraordinary circumstances leading to a failure. One must also estimate the frequency of such series of events occurring. Moreover, responsibility relationships can be determined for each element of the series of events, and the "initial" event can be retraced. A series of events of this nature for example was the progression of the water from the Petres levy breach to inundate Szeged in 1879 (see contemporary image in Figure 1). The water that flowed across a gap in a failed levy about 40 km from Szeged (then counting 80,000 inhabitants) had to break through several localization dykes to finally penetrate the circular levy protecting Szeged 6 days later. The city was completely devastated and 151 lives were lost.

One of the possible classifications of potential failure mechanisms of flood protection dykes is as follows:

- Overtopping.
- Dike breach following flood induced phenomena (slope slide, sand boils, softening up, seepage etc.)
- River-side erosion.

- Wave erosion (river-side and/or crest wave wash, overflow).
- Other failures (dispersive substances, human activities, peat subsoil, liquefaction, etc.).

The classification presented above is logically structured, aims to be comprehensive but is arbitrary. Nature is inventive and there are more conceivable failure mechanisms than those listed above.

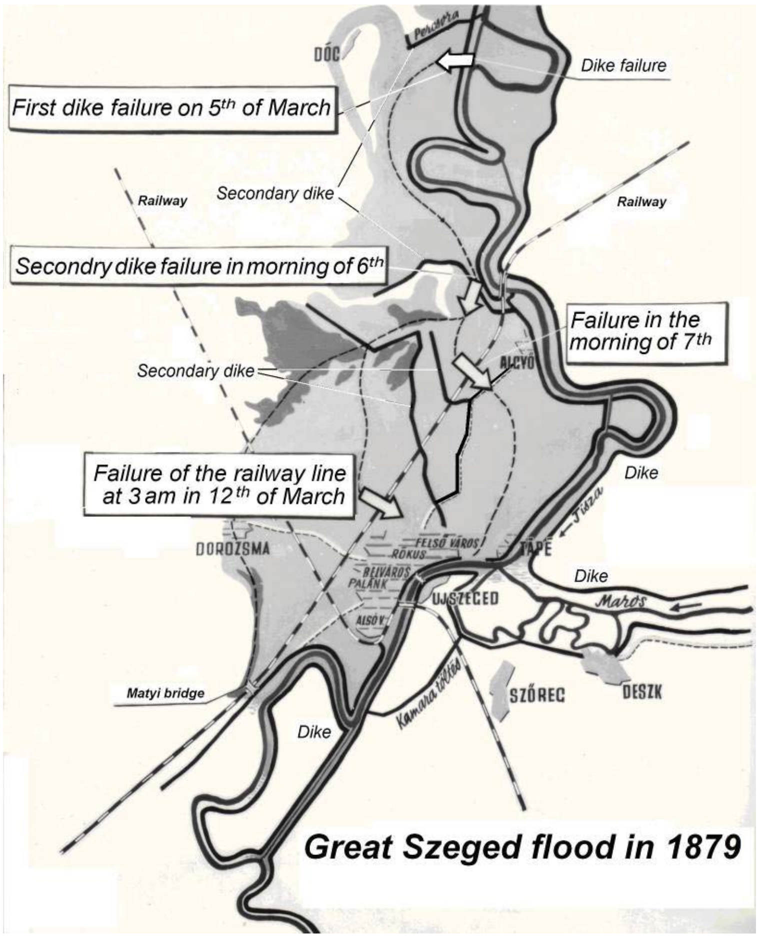


Figure 1. Processes leading up to the inundation of Szeged.

There are several ways to progress from failure mechanism estimations to the estimation of failure probabilities, but the result of the calculation yields the probability of failure for a section of identical behaviour (Nagy 1996). The accuracy of failure probability estimations varies: hence whenever several methods are used concurrently one has to ensure that they are homogeneous. Failure probability must be estimated for the design cross section of sections showing identical behaviour based on failure mechanisms. Methods for estimating failure probability (Nagy 1993):

- A technical estimate of dike failure probability is important in case no baseline data are available or in case something prevents producing them. A technical estimate may also rely on statistics collected about actual events, for instance dyke failure mechanism data.
- Analysing a tree diagram involves the creation of decision points for which occurrence probabilities are estimated.
- Subsequent sections of this article describe the use of historical data.
- The Monte Carlo simulation is a popular method for the comprehensive estimation of processes with calculation options.
- Calculation is the most sophisticated and most accurate version of estimation to be used in cases when engineering considerations have progressed to the stage of applying formula to describe a phenomenon.

These methods need to be coupled with failure mechanisms (Table 1) by determining which estimation is applicable for certain failure mechanisms (e.g. human activity matches the statistics of past events whilst slope slippages couple with calculation as shown in Table 1).

Table 1. Failure mechanism and related methods of estimation

Failure mechanism	Estimation methods
• Subsoil failure • Slope failure • Overtopping • Hydraulic soil failure • Wave erosion • Human activity • Crossing structures • Water side erosion • Dispersive clay • Earthquake	• Engineering estimation • Historical events • Decision tree • Monte-Carlo simulation • Calculation

4. Historical failure mechanisms

Historical events give us insight into the frequency of failure mechanisms, note, however, that those are based on actual events. Processing historical information helps eliminate less important failure mechanisms or ones that should be disregarded, but it also conceals unprecedented mechanisms.

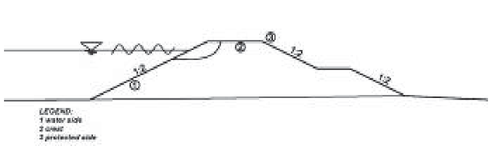
Figure 2. A very rare event at Korolevo/Királyháza, water side erosion (1998)

River-side scouring, for instance, had (for a long time) not been recognised as a probable failure mechanism in Hungary based on the assumption that water velocities offer no justification. The first data of this nature about dyke breaches in the Carpathian Basin were recorded during the flood of 1942, when "ice jammed around the pillars of the exploded bridge of Novi Sad/Újvidék and diverted the mainstream to the left bank, where the water under-washed the riverside and a 50 m wide and 550 m long section of the dyke breached" (Bonczos 1942). A picture taken along the section of the Tisza in the Ukraine during the flood of 1998 also demonstrates the importance of river-side scouring (Figure 2), which almost triggered a dyke breach. These events indicate that river-side scouring must be taken into account both as a potential and as an actually occurring failure mechanism (Nagy 2000). The result of estimations performed for various failure mechanisms provides the critical failure mechanism.

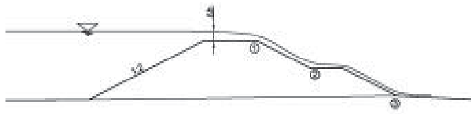
We lack substantive experience in respect of several of the potential failure mechanisms, and accordingly we are in no position to justify with calculations the way we need to expect such failures at a particular site:

- River-side scouring (Figure 1) can develop whenever water velocity is high at locations where water flowing at $v > 4$ m/s disintegrates part of the levy, especially where it is loose. River-side scouring is especially promoted by the speed of the river attacking the dyke or by turbulent flows developing along the dyke.
- Evidence exists for the presence of dispersive substances at several dyke locations in Hungary (Szepessy 1983). The likelihood of erosion with soil cavities is greater during high water levels. This failure mechanism is difficult to quantify and failure probability can be estimated from statistics taken of past events.
- Earthquakes may impact flood protection dykes in a variety of ways. Earthquakes may give rise to liquefaction of the granular substance below and in the dyke, may induce water swinging in the river, may get the slope

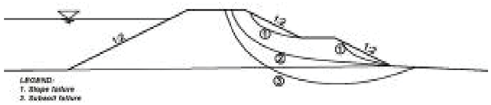
on the protected side to shift, etc. These consequences are more frequent when water level is high, but earthquakes rarely co-occur with high water level along flood protection dykes.



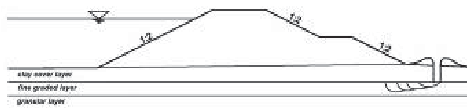
Wave erosion



Overtopping

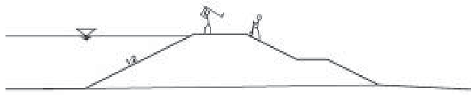


Slope or subsoil failure



Sand boil

Leakage



Human activity

Figure 3 Presents a historical overview of the most frequent failure mechanisms.

5. Historical dam and dike failure's

Studies by Sametz, Kroll, Middlebrooks, ICOLD, Baars provide a statistical evaluation of historical dyke and dam failures. Applying statistics of past events (Table 2) is a helpful tool for estimating failure probability, but the following problems are encountered:

- Are data suitable for statistical evaluation available for similar events?
- Is the data series large enough in terms of time and space?
- Does the series show a trend?

Brief remarks concerning Table 2:

- Information about the type of dyke (flood protection, canal embankment, sludge dam, major levy or seaside protection) covered by data analysis and occurrence of damage or failure are indicated in the two rows across the header of the table. Major differences between failures and damages.
- The differing nature of failure mechanisms is also obvious based on Table 2. Undoubtedly, construction defects, ice drifts, earthquakes, subsidence, etc. are reasons rather than mechanisms, (see Chapter 2). It is unquestionable that harmonising these categories would support

comparison and although the similarity between internal erosion and sand boil is known, one has to insist on the original term.

- Table 2 (Krol 1983) presents the distribution of damages observed in flood protection dykes in Poland, but it should be noted that the table presents damages only and mixes mechanisms with reasons.
- Sametz (1981) processed the results of a total of 115 dyke breaches in Austria, including a mixture of barrage dams, flood protection dykes and canal embankments (Table 2).
- The first study of breaches of *"large dams"* (Middlebrooks 1953) presents a summary of levy damages in North America (Table 2). Since that time, almost every country with large dams has produced statistics of this kind. Emphasis should be made of the breaches published by the International Commission on Large Dams (ICOLD) because of the volume of data.
- Mentions of overtopping feature most frequently in the statistics. Most of the breaches of both large dams and flood protection dykes resulted from an inappropriate calculation of discharge and water level and levies were not high enough in 32-67% of the cases.
- 24-60 % of the cases involve geotechnical problems relating to the soil or subsoil of the embankment as the failure mechanism (piping, soil fracture, erosion, etc.).
- Dutch flood fighters construct proper structures, as a communication by Baars (2009) reveals none of their failures could be attributed to structure in the period between 1134 and 2003, and their historical data are reliable as the failure mechanism of each of the 1735 collected dyke breaches is known.
- Sludge dam failures are just as varied as that of earth dams but they show a relatively high frequency of earthquakes and sludge liquefaction.
- The first ever data about failure make reference to the time of levy construction but do not offer information about the mechanism of the breach.
- The first written data about the failure of flood protection dykes in Japan originate from 758. A study of the 283 dyke breaches between 1947 and 1969 distinguishes only four categories (Fukunari 2008). Overtopping dominates with the number of cases at 231 (Table 2). Erosion, interpreted broadly (to include water side scouring, internal erosion, wave wash) occurred in 32 cases (11.3%) whilst piping and slope failure are grouped together to form a single category with 15 incidents (5.3%). There are 5 other dyke breach mechanisms on record. Fortunately, all of the mechanisms were known and structural failure was not recorded as a failure mechanism.

6. Historical data of dyke breaches in the carpathian basin

The descriptions of dike failure mechanisms are few and far between up to the mid 19th century. There were hardly any dikes (< 750-1000 km), and there were no witnesses of what happened as dikes were not manned. It was by the late 19th century that the concepts used to describe events credibly had developed, but the descriptions were mostly simple and schematic. It was around that time that the basic terms relating to failure mechanisms were defined: overtopping, wave wash, boil formation, etc. The most common failure mechanisms are presented in Figure 3.

Retaining the expressions used in the 19th century Table 3 presents the distribution of failure mechanisms in the Carpathian Basin and a variety of other information. Regarding an 18 year assessment of dike breaches, the percentage distribution of failure mechanisms across 1993, 2000 and 2010 as key years is typical of both data collection and failure processes.

Table 2. Mechanism of dykes and dams damage and failure described by various authors

Author	Sametz	Krol	Middlebrooks	ICOLD	ICOLD	Baars	Babb &	UNEP	Nagy	Nagy	Fukunari
Damage/**F**ailure	F	D	F	F	D	F	F	F	F	F	F
Year of publication	1981	1983	1953	1984	1974	2006	1968		2011	2011	2008
Type[1]	L/F/C	F	L	L	L	F/S	L	T	F	F	F
number	db	%	db	%	%	%	db	db	db	%	db
overtopping	43	32	61 (68)	$\times^3$	$\times^3$	67	60	20	925	$\times^3$	231
static failure	12										
dike/subsoil/contact seepage		25/25/0	(25)/0/16	27	25		29	0/0/11			
seepage			31								
structure failure			6 (63)		3		45	7	31	12	
settlement			8	13	8						
sand boil	40		29			1					32
hydraulic failure			5								
inner erosion				28	13						
erosion								3			
subsoil origin failure									51	19	
embankment origin failure									58	21	
compaction				5	4						
slope slide		3	14	9	9	5+3[2]		30			15
slope (wave) protection					9	6			29	11	
earthquake					2			19			
ice jam						11					
geotechnika											
human activity		7							64	24	
heavy rainfall											
foundation								10			
before first fill up			(23)				25				
rapid drown down			(5)				9				
first fill up			(4)				5				
other known	10	8	36	7	27	7			35	13	5
all together	105	100	206 (188)	100	100	100	173	100	1200	100	283

[1] Type: **L**arge dam, **F**lood dike, **T**ailing dam, **C**hannel embankment, **S**ea defenses
[2] Air side slope, Water side slope
[3] Without overtopping

Information is available about 84 of the dike breaches occurring in the floods after 1945[1] (Nagy 1993), and the number had almost doubled by 2000. 59 cases of overtopping are listed as the failure mechanisms with the largest number of instances (including 52 cases during the ice flood of 1956) (see Table 3). In 2000, 140 data were available for the same period. Percentages changed accordingly (Table 3). By 2010, the number of overtopping cases had grown and the percentage ratio of unknown mechanisms diminished owing first of all to the methodology of processing.

The failure mechanisms relating to the engineering activities presented in Table 3 (Nagy 1993, 2002, 2011) (hydraulic fracture of subsoil, failure of structure, loss of slope stability) show a low percentage of fracture.

Table 3. Distribution of the failure mechanisms of dike breaches in the Carpathian Basin

Year of the publication	**1993**	**2002**	**2002**	**2011**
Investigated period	**1945 – 1993**	**1945 – 1993**	**1800 - 2000**	**1564 – 2010**
Overtopping	61 %	57 %	19,5 %	32,4 %
Wave erosion	3 %	2 %	0,6%	1,0 %
Subsoil failure	14 %	16 %	2,2 %	1,8 %
Slope failure	10 %	6 %	1,8 %	2,0 %
Structure failure	3 %	1 %	1,3 %	1,1 %
Human activity	3 %	2 %	2,2 %	2,3 %
Other known	6 %	3 %	1,0 %	1,2 %
Not known	0 %	13 %	71,4 %	58,1 %
No. of data (piece)	**84**	**140**	**1816**	**2858**

An analysis of dike breaches must note that the load on flood protection dikes keeps increasing. The reasons for the extra load include first of all the fact that rivers run between dikes, secondly river regulation works and thirdly (and maybe most importantly) the change of flow conditions in upstream river sections. The extra load is manifested on the one hand by higher flood levels[2] and on the other hand by the simultaneous rise of the duration of floods.

The summary data presented about the Carpathian Basin in Tables 2 and 3 cover details concerning trends and changes. If the data are analysed over a time horizon, the following assertions are possible to make:

- the number of failures due to overtopping is diminishing both in terms of percentages and trend,

[1] Collecting historical data holds many surprises even if the target period is not so long ago as forgotten data may emerge and by no means can one be certain about the number of dike breaches as new ones come to light.

[2] Recorded flood levels rose by 3.3 m at Csongrád and 3.5 m at Szeged between 1830 and 1970 after flood protection was introduced along the river Tisza. Since then the rise of flood levels has surpassed four metres at both locations.

- failure due to overtopping is likely to occur along river sections with flashy regimes where watershed and discharge are small (i.e. to an extremely limited degree along the Danube and the downstream sections of the river Tisza),
- the likelihood of failure originating from the subsoil, namely from boil formation and soil fracture is expected to grow in the future,
- as the funds available for maintenance are reducing, the number of failures in the vicinity of structures is also expected to rise.

7. A few specific features of failure mechanisms

Several phenomena may trigger a failure mechanism in flood protection dikes. The failure mechanism associated with overtopping and wave over-splashing is the same because dike breaches develop as the crest, slope or levy toe are washed away on the protected side.

A failure mechanism may be the result of several errors that strengthen each other. Loose soil allows the formation of cavities, such as the ones caused by pests, which may lead onto seepage and piping and eventually dike failure.

A failure mechanism may develop in a variety of ways. For instance, the processes emanating from wave wash will indicate based on the relative difference between water level and the level of the dike crest at a single location whether the phenomenon involves washing away the slope or the crest or waves splashing over (flowing over the crest).

The failure of flood protection dikes may result from simultaneous and subsequent mechanisms. We do not have established methods for calculating the probability of failure for such circumstances, and estimates can in all probability be provided by approximation from conditional probabilities. Solving this problem requires additional effort.

The simultaneous and synchronised occurrence of several phenomena may strengthen the development of failure mechanisms. If, for instance, the conductivity of the subsoil is better than that of the dike, water flowing up from the subsoil may saturate the dike faster than through the dike itself. If that occurs, buoyancy attacks the protected part of the dike substantially faster than if it were caused by seepage.

Failure mechanisms may involve subsequent events, a chain of events that lead on to a dike breach. A chain of events allows us to trace the extraordinary circumstances leading to a failure. This may be a spatial process, which starts somewhere else (see 1879 disaster of the Szeged flood), or may occur at a single location (Tarpa dike breach in 2001) in a staged manner. Moreover, failure modes must be determined for each element of the series of events to allow inferences from the "initial" event to subsequent events. This is because there are certain defective structural components or erroneous activities that emanate from certain parts of the system and the errors of people working in the system. Frequency occurrence must be estimated separately for each component event of series of events leading to a failure (Nagy, 2000).

As yet, current professional approaches ignore the simultaneous occurrence or the mutually strengthening effect of two or more failure mechanisms. For instance, wave wash on the water side slope shortens the travel of seepage and increases hydraulic gradient, which promote hydraulic fracturing or slippage of the slope on the protected side. Our studies assume that modes of failure are independent of each other. Additional research is needed to allow us to create models and quantifications of simultaneity and subsequency.

8. Summary

It is possible to estimate the probability of failure mechanisms associated with the design cross section of sections with identical behaviour; failure probability can be calculated for a single cross section, for a dike section based on cross sections and for a whole flood area. Everything depends on initial data. Errors in initial data will determine the final outcome calculated by the system. That is why the reliability of initial data requires utmost attention.

It is recommended that we use technical estimates (based frequently on averaging and/or supplementary engineering calculations) and statistics of past events for estimating the probability of failure for failure mechanisms that are not yet covered by a method of calculation (water side scouring, human activity, crossings, dispersive soil, etc.) (Nagy 1996, 2000).

Regardless of the type of dike involved (Table 2), most dike breaches were a consequence of overtopping. The dike simply was not high enough compared to the level of water. Crest height has always been calculated in accordance with the technical advancement of the age. Accordingly, overtopping was a dominating feature during subsequent floods due to poor safety strategies.

The guiding principle for risk calculation requires that we study

danger – mechanism – failure – consequences.

As long as a reliability analysis of individual cross sections of the full system of flood protection is not available, no fully fledged quantitative risk calculation is possible. However, as the failure probability of a dike cross section can be determined using geotechnical and stability calculations, the failure probability of a flood area can be defined using mathematical tools. That allows us to evaluate the risk associated with a flood area by dimensioning based on the reliability principle and we can use development opportunities purposefully. The statistical evaluation of historical data and past events assists us in these efforts.

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