WP 6: Monitoring and Case Study

Detailed Technical Report
on the collation and analysis of dike breach data with regards to formation process and location factors

Conclusions

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1. INTRODUCTION

The uniqueness of the topological features of Hungary (93000 km$^2$) in the Carpathian Basin (~450000 km$^2$) is matched by the uniqueness of the tremendous effort the people living here undertook in flood control to improve living conditions. The topographically adjusted flood control system boasts 4200 km of levees in Hungary and dikes constructed along more than 11,000 km in the Carpathian Basin.

Technical, economic, social and political problems, which had been left unsolved, always surfaced when large floods hit and dikes were destroyed. Numerous interesting lessons can be learnt from dike breaches, one of which concerns final breach length and the development of scour pits (Nagy 2000, 2001). Both are important and are in close relation to the shape of the dike breaches, therefore they are important part of the IMPACT project. The historical research has identified 1245 dike breaches in Hungary, including 556 case where the length of the breach is known.$^1$

1.1. Flood hazard in the Carpathian-Basin

Under the particular physico-geographic conditions of Carpathian-basin, important and steadily growing interests have been attached to flood control for centuries. The fundamental cause of the grave flood hazard is that the overwhelmingly plain country is situated in the deepest part of the Carpathian Basin, where the flood waves rushing down from the surrounding Carpathian and Alpine headwater catchments are slowed down, overtake and coincide with each other resulting often in high river stages of extended duration. Owing to the climate and the physico-geographic situation floods are liable to occur virtually on any Hungarian river in any season of the year. The largest tributary to the Danube is river Tisza draining the eastern part of Carpathian-basin.

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$^1$ It is worth noting that the study focussed exclusively on earthwork levees.
Within the territory of Hungary only Rába and Rábca, as well as Mura and Dráva (forming national border with Slovenia and Croatia) tributaries to the Danube, Szamos, Bodrog, Hármas-Körös (Triple-Körös, resulting as confluence of Sebes- and Kettős /Double/-Körös as receiver of Fekete /Black/- and Fehér /White/-Körös) and Maros in the Tisza Valley can be considered as larger rivers. Characteristic discharges of these rivers are summarised in Table 1. Smaller rivers are Sajó, Hernád, Tarna and Zagyva in the Tisza Valley, and Sió, tributary of the Danube.

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<th>River</th>
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<th>$Q_{\text{max}}$</th>
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<td>Záhony</td>
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<td>4.5</td>
<td>1800</td>
<td>400</td>
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<tr>
<td>Maros</td>
<td>Makó</td>
<td>22.0</td>
<td>2450</td>
<td>111</td>
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</table>

Table 1. Characteristic discharges of main Hungarian rivers

In Hungary - situated in the deepest part of the Carpathian-basin - flood plains make up 22.8 per cent (21,248 km²) of the country. A survey and comprehensive economic assessment completed in 1994 has shown 2.5 million people of round 700 communities in the protected flood plains to be exposed to flood hazard. These plains comprise 1.8 million hectares or one-third of the arable lands in the country, over 2,000 industrial plants, 32 per cent of the railway lines and 15 per cent of the road network. Some 25 per cent of the gross domestic product is generated in this area. The national assets accumulated here have been estimated at USD 11,2 billion at the 1994 price level.

1.2. Dams and flood embankments

A study of dike failures should first of all differentiate between dikes or levees built along riverbanks to protect against floods and dams or barrages running perpendicularly to a river. There are differences in structure, material and size, and the consequences of a failure also diverge.
This collection of data refers only to flood embankments (dikes/levees) constructed along rivers. The table is also suitable for the collection of data on dam breaks, in this case it should be noted in column 58. The collection does not extend to failures of dikes of ponds, banquettes of drainage or irrigation canals, etc.

A retrospective study and the statistical processing of the reasons behind dike failures have contributed to increasing the safety of dike designs and to reducing substantially the likelihood of major dikes failing. An analysis of the failures of major dikes requires a breakdown by dike material, such as concrete (arched and weight), riprap, walled, earthwork embankments, etc. and a separate analysis of the cause of failure.

When a barrage (or dam) fails, a higher wave of flood will move lengthwise through relatively narrow cross-section along a valley. The devastating effect of the initial wave is especially important, as that inflicts most of the damage. ICOLD\textsuperscript{2} registers hundreds of dam failures (ICOLD 1981, 1984, 1995, ASCE/USCOLD 1988). A dam is normally located in one of the narrows of a valley and the spilling water may wash away most of the dam.

Long dikes of almost identical height running parallel to a river flowing across a plain pose different hazards. Water spilling across a breach will fan out with its flow determined by the topographical conditions of the terrain on the protected side. If that occurs, the volume of the spillage, which depends heavily on the width of the breach, plays an important role. The width of the opening developing on a failed levee is of great relevance therefore.

Dike failures are the subject matter of IMPACT, a project conducted by the European Union (between 2002 and 2004). The research project seeks to construct a temporal model of breach formation, how the shape and depth of openings is changing in time to see what happens under natural conditions during especially the first let’s say thirty minutes of a levee breach. The project studies dike failures using on site large scale (1:1) tests, laboratory tests on a scale of 1:10 and computer modelling.

Neither of these methods will, however, be indicative of the expected terminal length of a developing levee breach despite the importance of localization from the perspective of protecting lives and assets. The terminal width of a levee breach depends on a number of factors that do not or hardly if at all lend themselves to modelling.

2. IMPLEMENTATION OF THE TASKS PRESCRIBED BY THE DESCRIPTION OF WORK

2.1. Identification of the tasks

According to the DOW of the project, tasks of Partner 11 (H-EUR Aqua) were the followings:

D6.5 Collation of case study data relating to breach events in Hungary. Provision of data in agreed format (the same task was assigned related to breach events in the Czech Republic for WP6 leader Geo).

D6.6 Analysis of Czech and Hungarian breach data with regards to formation process and location factors.

D6.7 Collation of case study data relating to extreme flood events in Hungary. Provision of data for use in modelling and calibration (the same task was assigned related to breach events in the Czech Republic for WP6 leader Geo).

\textsuperscript{2} International Commission on Large Dams
2.2. Implementation

2.2.1. Preparatory works

It has to be mentioned that the IMPACT-ADD partners incl. H-EURAqua joined and started their project activity in Mn 13 (Dec. 2002).

Designing the database format

Database format designing for the whole WP6 was assigned to and done by H-EURAqua. This activity included:

- determination of the types of data to be collected and co-ordination with project partners,
- determination of the structure as well as organisation and establishment of data base

The first version of the database was compiled and sent to project partners for evaluation and comments still on 21 December 2002 (Mn 13). As a result of late comments received the redefinition of the scope of data to be collected and creation of database v1.1 was prepared in Excel and sent to project partners on 26/03/2003 (Mn 17). After receipt of the final comments and proposals the modified final breach data collection sheet v1.2 was sent out to partners with explanation on 05/06/2003 (Mn 19).

According to our intention, the data to be collected extends to the followings:

- **Date** (columns 1-2): year, dd/mm/hrs/min
- **Location** (columns 3-6): country, river name, bank, (L - left; R - right bank), stationing (for example 32+068).
- **Breach data** (columns 7-10): pieces, final length of breach, final depth below dike crest, scour pit depth
- **Origin of the flood** causing failure (columns 11-14): snowmelt, rainfall, ice jam, other or not well identified
- **Failure mechanism** classified into 8 groups (columns 15-30): overtopping, stability loss of embankment (due to seepage, leakage, saturation of the dike body and/or foundation), wave erosion, scouring from water side, failure at crossing structure, deliberate (illegal) cut, stability loss of foundation due to hydraulic failure, other known, unidentified
- **Cause of breach** (columns 31-36): bad material, bad design, bad construction, bad maintenance, lack of appropriate emergency operation, no information
- **Flood parameters** (columns 37-44): water level above base at the breach and below the peak, respectively, breach happened before or after peak of flood wave, river flow rate, return period of flood, river flow velocity, flow through breach (estimated max.)
- **Data on damages** (columns 45-49): size of area inundated, number of casualties, houses destroyed, other losses, estimated total loss (ME)
- **Embankment parameters** (columns 50-54): height of dike, crest width, water side slope, air side slope, base width
- **Soil types** (columns 55-57) according to BS soil categorisation: dike body, (main characteristics of the strata; main strata are: permeable, transitional, impermeable, with some physical characterisation as available), foundation soil layers, depth and soil nomination, (stratification of foundation soil; depth of different characteristic layers as available),
- **River morphology** (short characterisation on the bend conditions near the breach)
- **Remarks and literature** (source of the information)

Preparation of the work plan

This activity included preparation for and organisation of the conditions of data collection, including a preliminary collation of relevant information on and assessment of the potential data sources. In this period beside the national and county libraries and archives, special attention was paid to the Museum and Archive of Water Affairs to find traces of the historical records of the old Flood Prevention and Drainage Associations ceased just after World War II, and of the professional papers as well as legal and technical regulations of the 19th and early 20th century. Finally the existing regional water directorates were interviewed on their collection of old plans, papers.
Table: IMPACT project – detailed working plan – Partner 11: H-EURAqua

<table>
<thead>
<tr>
<th>Activity</th>
<th>Project Months</th>
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<tr>
<td>13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36</td>
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<tr>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24</td>
<td></td>
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<tr>
<td>Calendar months</td>
<td>2002 2003 2004</td>
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</table>

- Development of database format
- Data collection planning
- Preliminary evaluation system
- Archive of Water Affairs
- National Széchenyi Library
- Parliamentary Library
- Museum of Water Affairs
- Northern-Transdanubia*
- Upper-Tisza Valley*
- Northern Hungary*
- Körös-Valley*
- Trans-Tisza region*
- Central-Tisza-Valley*
- Lower-Tisza-Valley*
- Central-Danube Valley*
- Lower-Danube Valley*
- Southern-Transdanubia*
- Evaluation system fine tuning
- Analysis of collected data
- Additional data collection
- IMPACT Workshops
- Partner 11 draft report
- Partner 11 final report

Legend:  actual activity exceeding those of previously planned

*Note: data collection is to be performed by the investigation of available information at county libraries, District Water Authorities, Water Management Associations and local water management museums and public collections.
As a result of this preliminary assessment, taking also the work plan of the IMPACT project into consideration (especially the distribution of man-months during the whole project), the working programme in the form of a GANNT chart was finalised in Mn 16 (see Figure 1.). Parallel to this, still in the same month the data collection started. It has to be admitted that we could not wait for the finalisation of the data collection sheet (which was too slow in the lack of adequate communication and response from project coordinator and partners) due to time constraints.

H-EURAqua undertook to collect and analyse data of historical dike breaches of the past 200 years across Hungary in the assumption that although historical data may rather be incomplete, due to the high number of samples (estimated to be over 800) the possibility of deriving statistical conclusions will be given.

3. DATA COLLECTION AND MANAGEMENT

3.1. Data Collection
While the first four month (Mn 15-19) of data collation focused primarily on literature research in national libraries, museums and archives, from June 2003 (Mn 19) the twelve district water authorities of Hungary, as well as county libraries of the given region were visited. The data collected were continuously loaded in the agreed database format. The Excel sheets of data of Mn 12-22 were sent to project partners in Mn 23, data sheets of Mn 13-26 in Mn 27 as e-mail attachments. Data collection was finished in May 2004 (Mn 30) and the row datasheet was sent by e-mail to partners in the same month. Additional field check of data supplemented with secondary data collection was needed as a result of crosschecking in Mn 32 and 33.

HEURAqua submitted D6.7 report on Collation of Case Studies on Extreme Flood Events in Hungary on 17 April 2004 (Mn 29), containing the description of the circumstances and conditions of the most remarkable breaches of the past 25 years in Hungary, namely the breach at Hosszúfok, Kettős-Körös River (1980), the breach at Surány, Danube River (1991), the breach of the Fehér-Körös left bank dike at the Gyula I. Pump Station (1995), and the breaches at Tarpa, right bank of the Tisza River (2001). The report contains all available data of these events incl. hydrology of the floods, detailed geotechnical data, description of the events and that of the emergency activities.

Data collection results from the Czech Republic were distributed to interested partners of the project in January 2004 (Mn 26) on CD-ROMs as the input for the other WPs.

3.2. Collected data

There is nothing to suggest that statistics of the failures of flood defenses exist anywhere on this earth. This data collection could be the first step towards a subsequent project of international scope and the related processing. As opposed to our initial estimation that data of about 700-800 dike failures would be found, we actually managed to collect some information about one and a half times as many failures, which was a significant positive variation. Data collection requires calm and balanced circumstances in the archives. We estimate that with twice as much time at our hands, the pool of available data (not necessarily about the length of dike failures) would increase by 20-25%.
The database (collation of which has been closed in Aug 2004) contains information on 1245 breaches that happened on the present territory of Hungary. Early in the 19th century isolated areas were protected by levees of 340 km total length, which increased to 720 km by 1850. The low number of failures before 1850 is attributable to the shortness of the levees. The number of failures (986 breaches as long as 1900) demonstrates clearly that the large-scale flood control project launched in 1845 was not fully successful up to the turn of the century. The number of failures in this period surpasses former expectations.

Data collection was extended to the following main groups of information:
- Date of breach
- Location of breach
- Breach data
- Origin of the flood causing failure
- Failure mechanism
- Cause of breach
- Flood parameters
- Data on damages
- Embankment parameters
- Soil types,
- River morphology
- Remarks and literature

The sources were reviewed with the aim of finding the following data on levee failures (some remarks and explanations for users are in bracket).

3.2.1. BASIC DATA, (columns 1-2 in the summarising table of the database)
- year,
- day/month/hrs/min
Considerable difficulties have been encountered in identifying ancient, no more used names of communities, sections, etc. mentioned by two authors under different names. This problem may have resulted in some overlaps in the table.

3.2.2. LOCATION OF THE BREACH, (columns 3-6):
- country,
- river name,
- bank, (L - left; R - right bank),
- stationing (for example 32+068).

3.2.3. BREACH DATA, (columns 7-10):
- pieces,
- final length of breach,
- final depth below dike crest, (final depth of breach below dike crest (m); including the depth of scour pit),
- scour pit depth (measured from the level of terrain at the dry side toe).

3.2.4. ORIGIN OF THE FLOOD CAUSING FAILURE (columns 11-14):
In case the origin of flood is a combination of two or three of the given reasons, each of them had to be marked with number 1.
- Snowmelt, 412 pieces,
– Rainfall, 223 pieces,
– Ice jam, 344 pieces,
– Other or not identified 346 pieces.

Total: 1325 pieces. In several cases 2-3 different origins were given in the source literature.

3.2.5. Failure mechanism classified into 8 groups (columns 15-25):

– overtopping (means water level exceeding the dike crest and in the lack of emergency heightening the overflowing water washed the dike body away),
– stability loss of embankment (due to seepage, leakage, saturation of the dike body and/or foundation) - uncontrolled seepage in the dike body, including contour seepage in case of not proper foundation of reinforcement, that may lead to concentrated saturation and thus slope sliding)
– wave scour (dike washed away due to uncontrolled erosion originating from wave impact and/or scouring from water side),
– crossing structure (dike breach caused by the failure of a crossing structure (gated sluice, culvert, pipeline, etc),
– deliberate (illegal) cutting
– stability loss of foundation due to hydraulic failure,
– other known,
– unidentified.

The deliberate cuts do not include officially approved diversions to emergency reservoirs to lower peak stages. Evidently, neither the cuts to drain these after the flood belong to this group.

3.2.6. Cause of breach, (columns 26-31)

– Bad material,
– Bad design,
– Bad construction,
– Bad maintenance,
– Lack of appropriate emergency operation,
– No information.

3.2.7. Flood parameters, (columns 32-36)

– breach happened before or after peak of flood wave,
– river flow rate,
– return period of flood,
– river flow velocity,
– flow through breach (estimated max.)

3.2.8. Data on damages, (columns 37-41):

– size of area inundated (ha),
– number of casualties,
– houses destroyed,
– other losses,
– estimated total loss (M€)

3.2.9. Embankment parameters, (columns 42-46 in the data base)

– height of dike, (height of dike crest over the terrain level at the dry side toe),
– crest width,
– water side slope, (ratio of height/width)
– air side slope, (ratio of height/width)
– berm width.

For long years in the 19th and in the early 20th century, safety meant identical dike size (identical crest width, identical slope inclination) in Hungary. Dikes were built and strengthened in line with standardized cross sections along river sections, which were the competence of a single flood control society (Figure 2).

3.2.10. SOIL TYPES, ACCORDING TO BS SOIL CATEGORISATION, (columns 47-49)
– dike body, (main characteristics of the strata; main strata are: permeable, transitional, impermeable, with some physical characterisation as available),
– foundation soil layers, depth and soil nomination, (stratification of foundation soil; depth of different characteristic layers as available)

3.2.11. RIVER MORPHOLOGY DESCRIPTION, (short characterisation on the bend conditions near the breach (convex or concave bend, distance of mean river bed edge from the dike, etc.)

To describe the river morphology of historical breaches is difficult for three reasons:
– meandering and ‘migration’ of rivers in alluvial floodplains may be substantial even in the course of 30 years,
– there were 106 and 57 shortcuts along the Tisza and the Körös rivers, respectively, in the 19th century, there were fewer but longer individual shortcuts along the Danube,
– the impact of river morphology is smaller when a river occasionally flows at a distance of several hundred meters from the dike.
3.2.12. REMARKS AND LITERATURE

Remarks, other circumstances, notes, (important data of dike history relevant to the breach, like year of construction, reinforcements, phenomena observed earlier, etc.). Insert photo(s) if available in .jpg format). Literature, the source of the information.

3.3. Data Management and Evaluation, Homogeneity Test

Scientifically accepted archival investigation and systematization of historical data is a very time consuming activity. However, to meet the demands of management and collection of historical data during our work was a high priority. Despite conscious efforts, during data collection there was no way to influence how much data one succeeded in collecting about a certain item. The work performed allows us to declare that historical data are incomplete.

Crosschecking of data in case of contradictions of the discovered data sources (literatures) and closer identification of historical breach sites was repeatedly done until the data were not confirmed by independent sources. The data collected only lent themselves to evaluation if several authors provided control data for the same item. We have several sources of data regarding the characteristics of certain dike failures. If a discrepancy was found, we included each of them in the collected dataset. That explains why a certain cell may contain more figures.

Statistical evaluation of data types, formation of data series, assessment of interdependence of data and homogeneity tests were performed and extreme values were eliminated from the dataset selected for analysis.

Data provided by the Czech colleagues showed some anomalies and inconsistency therefore interim discussions were needed for clarification. Analysis of these rather short and incomplete data series could not provide with any exciting results beyond distribution of failure mechanisms and causes, relations of breach length vs height of overflow and river flow rate indicated very poor correlations.

3.4. Data Analysis

Analysis of the collected data took place from Mn 23 to Mn 34 with minor interruptions. Finally, the preliminary database has somewhat been shrunken, because of the lack of some specific data. Comparison of lists provided under 2.2.1. and 3.2. shows that concerning failure mechanism saturation of dike body and/or foundation as well as wave erosion and scouring from water side was merged, from among flood parameters water level above base at the breach and below the peak, respectively had to be deleted, among embankment parameters base width has been replaced by berm width (base width can be calculated from the available other data).

3.5. Evaluation of Collected Data

Data related to soil types of the embankment and/or the foundation layers are in general very poor. Related to the total number of the identified breaches (1245) geotechnical information was found only in 5.78% of the cases. Especially poor is the information in the case of the breaches before 1954 (1.06%), however soil types are characterised in 51.3% of the cases of breaches of the past 50 years.

This means that we have information on soil types in 12 cases before 1954 (from among those in 8 cases the information available is incomplete) and in 60 cases after (in 5 cases the information is incomplete). Although the latter number seems reasonably high, this type of
information is rather generalised, the categorisation or estimation is rough, since the inhomogeneity of flood embankments of ours, which have several times been heightened and reinforced, thus their cross section is similar to that of the onion. Therefore the information on soil types is to be handled with very special care and is suitable to draw rough conclusions only.

Availability of other parameters is much better, but is still poor in the majority of the cases. Concerning flood parameters there are 5 cases with complete information, all of them from the latest years, while in 147 cases (114 before 1954) there are useful partial data. Evaluating the embankment parameters we have to conclude that there is only partial information available in 160 cases (137 before 1954) and total description on the geometry of the dikes is available in 193 cases (101 before 1954).

Complete data series of events comprising detailed flood parameters, embankment parameters and soil type characterisation are too rare. However, availability of partial flood parameters allows us to investigate quite a high number of cases (number of data involved into analysis is indicated in the diagrams). The major problem is that from the 32 cases of the past 50 years 23 is related to the ice jam flood in February 1956, and the conditions of these are not comparable to the others for at least two reasons:

− soil was frozen due to extreme whether conditions, both in record low temperatures and the duration of the frost, and
− although the flood crest was the highest ever recorded, it was due to series of ice dams and the river discharge, consequently the volume of water flow through the breaches was relatively low.

We gave detailed description from the 4 best-explored breach events in our D6.7 report.

Parameters concerning date, final length, cause, and failure mechanism of breach are best available.

4. DISTRIBUTION OF DIKE FAILURES IN HUNGARY ACCORDING TO THEIR FAILURE MECHANISM

In the frames of the D6.5 task of the project we have made an extensive investigation on the dike breaches in Hungary. Investigation of historical records in central and county libraries and archives, as well as the collection of the Museum of Water Affairs, integrated databases and contingency plans of the District Water Authorities, etc. allowed us to identify 1245 different breaches from 1802 up to now.

Literature explored indicated 1266 failure mechanism for the 1245 breaches. From 1241 breaches the failure mechanism is known in 506 cases, that is 40% of the total. The distribution of those known is illustrated in Figure 3.

<table>
<thead>
<tr>
<th>Failure mechanism</th>
<th>Pieces</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overtopping</td>
<td>370</td>
<td>29.2 %</td>
</tr>
<tr>
<td>Subsoil failure</td>
<td>37</td>
<td>2.9 %</td>
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<tr>
<td>Deliberate cut</td>
<td>17</td>
<td>1.3 %</td>
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<td>Wave scour</td>
<td>14</td>
<td>1.1 %</td>
</tr>
<tr>
<td>Structure failure</td>
<td>21</td>
<td>1.7 %</td>
</tr>
<tr>
<td>Loss of dike stability</td>
<td>34</td>
<td>2.7 %</td>
</tr>
<tr>
<td>Other known</td>
<td>13</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Unidentified</td>
<td>760</td>
<td>60.0 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1266</strong></td>
<td></td>
</tr>
</tbody>
</table>
The figures on deliberate (illegal) cuts, wave scouring and culvert failures are probably correct, in that, as special cases, these were mentioned repeatedly in the contemporary and more recent press and in the professional literature as well.

Distribution of the failure mechanism of the breaches in those cases where and when the causes of the dike breach could be identified is shown in Fig. 4. The graph clearly shows that the majority of the breaches were caused by overtopping, which lead to the continuous raising and reinforcement of the dikes, as can be seen in Fig. 2.
4.1. Dike failures of the past 50 years in Hungary

The floods during the past 50 years (1954-2004) have caused 117 embankment failures, of which 72 were due to overtopping, 21 to hydraulic soil failure, 10 to stability loss of embankment and 2 to leakage along structures, while the failure mechanism could not be identified in 12 cases (Figure 5). Although the number or the proportion of overtopping is still quite high, it can be explained by the 1956 ice-jam flood on the Danube (33 cases), the flood in 1963 along the relatively small Tarna river and its tributaries originating from the Mátra mountains (16), the extreme floods of smaller tributaries, the Répce and Lajta of the Danube in 1965, causing 8 cases (while the Great Flood of the Danube was successfully defended in Hungary). Further 4 cases occurred in 1972 along the river Mura, 2 in 1974 along the quite torrential Fekete-Körös, another one here again in 1981, finally the extreme flood of the Upper-Tisza in 2001 resulted in 2 breaches along the Tisza right bank in Bereg and another 2 along its tributary, the Túr.

![Diagram showing distribution of identified failure mechanisms of the breaches of Hungarian flood dikes (1954-2004).](image)

As a consequence of the continuous heightening of the levees, the type of failure has been changed. While in the earlier period of the history of flood protection the main danger and cause of damages was overtopping of the river dikes, which was followed by the complete erosion of the dike body itself, the heightening of the dikes lead to growing exposure to the foundation soil supporting development of hydraulic soil failure, boils and piping, while the growing duration of floods raised the risk of dike saturation (Fig. 5.).

The operation of barrage systems have modified also the falling limb of the flood hydrographs (the water levels are falling at faster rates), which may cause slumping of the waterside slopes of embankments and natural river banks alike.
5. THE SHAPE OF LEVEE BREACHES

Levee breaches have typical shape. A study of the photographs taken of dike failures that occurred in recent decades either in Hungary or abroad reveals several similarities in the shape of levee breaches, regardless on the location (country, river) of the given breach (Photo 1 – 19 – photos are in Annex). Although dikes and frequently even the top layer of the subsoil are washed away when a levee fails, local circumstances and soil conditions can be relatively properly reconstructed.

The remaining levee stubs are almost always vertical. Their direction is either perpendicular to the longitudinal axis of the levee or the opening narrows towards the protected side at a slight degree of inclination. The inclination of the plane of the levee stub is usually 0-25° (Photo 1 - 19).

A study of levee breach final cross sections shows that water washes the full section of the levee away in almost every case. Nevertheless, a small piece of earth normally remains at the water side levee toe, and it reduces the height of overflow as the water falls over it (Figure 6).

![Fig. 6. The cross section of a breach upon dike failure and during the development of an opening](image)

This piece of earth is frequently called “bar” (Photo 1 and 13 - 16.). The formation of the bar is normally due to the low velocity of the flow (at the wet side levee toe) near the original ground surface in the failed section, hence the water cannot wash the “bar” away. That was a common feature in each case when no pit was scoured and whenever a scoured pit failed to spread to the wet side.

A dike fails at a single “point”. Practical observations suggest that the vertical wall of earth that forms at the edge of a breach at the levee stub plays a key role in widening the breach (Photo 1 - 19). The water flowing by the edge of the opening carves into the levee toe and the dike above it falls to form a vertical wall yet again. The greater the velocity of the flow, the faster the flowing water will wear the edge of the levee stub away and the faster process of repeated wall formation will be. If the material of the levee toe is such that even flows of lower velocity can disintegrate, the breach in the failed dike will widen. Such soil types may include erosive soils, poorly compacted soils and disperse soils.

Non-cohesive or fine grainy soils (with low cohesion) at the edge of an opening may wash away at substantially smaller flow velocity than highly cohesive soils.
5.1. Levee Breach Length

Practical experience suggests that levee breach length depends on the factors summarized in the formula below:

\[ L = L(H, G, R, S, Q, A, T) \]

where
- \( H \) = head over the weir (see more in sub-chapter 5.3.),
- \( G \) = the dimensions and geotechnical properties of the dike (see more in sub-chapter 5.4.),
- \( R \) = river flow conditions in the vicinity of breach (see more in section 5.5.1),
- \( S \) = topographic conditions on the protected side (see more in section 5.5.2.),
- \( Q \) = the discharge of the river (see more in section 5.5.3),
- \( A \) = the activity of flood fighters (see more in Chapter 7),
- \( T \) = the function of time (see more in sub-chapter 5.6.).

Factors three, four and five can be merged. Once they are merged, one may work with the vector sum of the factors determining the flow of the water reaching and flowing out through a levee breach. Although it is easy to comprehend the effect of the factors listed above, their role deserves illustration through a few practical examples (Photo 2, 4, 7, 12, and 15).

5.2. The Length of Levee Breaches in Hungary

The number of dike failures identified in Hungary by historical studies is 1245, including 559 (45 %) with known length. Table 2 shows the breakdown of the number and length of breaches by river. Different authors recorded alternative lengths for 6 of the 559 dike breaches of identified length.

<table>
<thead>
<tr>
<th>River</th>
<th>Dike breach</th>
<th>Identified length</th>
<th>Total length</th>
<th>Average length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pieces</td>
<td>pieces</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>Danube</td>
<td>270</td>
<td>78</td>
<td>8189</td>
<td>104</td>
</tr>
<tr>
<td>Tisza</td>
<td>219</td>
<td>96</td>
<td>9192</td>
<td>95</td>
</tr>
<tr>
<td>Tributaries</td>
<td>539</td>
<td>290</td>
<td>12422</td>
<td>42</td>
</tr>
<tr>
<td>Small rivers</td>
<td>217</td>
<td>95</td>
<td>3424</td>
<td>35</td>
</tr>
<tr>
<td>Total:</td>
<td>1245</td>
<td>559</td>
<td>33227</td>
<td>59</td>
</tr>
</tbody>
</table>

*Table 2. Number and length of breaches*

The longest levee breaches that occurred in Hungary are presented in Table 3. Practically, each one of these dike failures
- occurred along a river with high discharge, i.e. there were large volumes of water for replenishment,
- occurred in the 19th century, when levees were very much inferior in size,
- inundated spacious food areas, i.e. large volumes of water could spill across the breaches.

Of the 329 dike failures along the Hungarian Tisza in the past 150 years, breach length is known in the case of only 142 instances. Total length reaches almost 11.5 km, which brings average length to 81 meters.

\[3\] As a boundary condition, we should mention that this study is limited to dikes made of earth to control floods.
The first aspect of studying the length of dike failures is to see whether or not the longitudinal profile of the river shows some alteration or regularity. The River Tisza, which is 945 km in length, flows between levees along 800 kilometres practically downstream from Huszt (Khust, Ukraine). In Hungary the River Tisza flows in a length of approximately 600 km between 153 and 744 fkm sections. Figure 7. presents the length of dike failures distributed by the profiling of the River Tisza. Average length of breaches along the Upper-Tisza does not deviate significantly from those of Lower-Tisza, although both the linear and exponential trend line show a slight rise towards the recipient, e.g. the Danube, increase is not significant. The exponential trend line indicates the effect of the Danube, however, it should be mentioned that the backwater effect of the recipient is felt in fact along a longer stretch.

![Fig. 7. Dike failure length along the longitudinal section of the Tisza](image-url)
A logarithmic trend reveals that the width of dike breaches occurred along the Danube does not vary significantly with the location of the breach, whilst an exponential trend shows that smaller widths are found as we move upstream (Figure 8). Plotting by longitudinal section is only possible for the Danube and the Tisza rivers.

\[
y = -0.544 \ln(rkm) + 116
\]

\[
y = 251 e^{-0.0008(rkm)}
\]

\[
R^2 = 9E-08
\]

\[
R^2 = 0.012
\]

\[y = -0.544 \ln (rkm) + 116\]

\[y = 251 e^{-0.0008(rkm)}\]

\[R^2 = 9E-08\]

\[R^2 = 0.012\]

\[\text{breach length (m)}\]

\[\text{river section (river km)}\]

\[\text{Serbia and Croatia}\]

\[\text{Hungary}\]

\[\text{Austria and Slovakia}\]

\[\text{1432 km section}\]

\[\text{1850 km section}\]

\[\text{750 758 700}\]

\[\text{700}\]

\[\text{1800 1900}\]

\[\text{1800 1900}\]

\[\text{1400 1500 1600 1700 1800 1900}\]

\[\text{0 50 100 150 200 250 300 350 400}\]

\[\text{breach length (m)}\]

\[\text{river section (river km)}\]

\[\text{Fig. 8. Dike failure length along the longitudinal section of the Danube}\]

### 5.3. The Overflow Height of Spilling Water

After a breach occurs, there is an unbroken and dynamic increase of overflow height. River water level does not change as fast as the breach deepens and widens. The availability of data concerning depth and width variations is extremely limited despite the large number of breaches. Dike breaches can be described in terms of their final condition, i.e. by the terminal width of a breach that does not grow any more. In this situation the height of the head of overflowing water can be described using the weir formula, where the height of overflow can be defined as shown in Figure 6, rather than by calculating the difference between water level on the water side and on the protected side. The quantity of the overflow will be proportionate to the height of overflow on the power of 3/2.

It is beyond any doubt that overflows with the weir head above three meters will have substantially more destructive power and boundary shear than water where the head over the weir is single meter only.

Consequently, doing nothing else but reducing the height of overflow in the case of a dike failure will achieve a lot. Overflow volume will be reduced and smaller areas will get inundated. Opportunities for intervention present themselves of the protected side first of all but effective interventions can also be made on the wet side as well.

Constructing a stilling basin on the protected side may reduce overflow height. The flood that hit the Middle Tisza in 2000 is an example. The slope of the protected side of the levee on the right hand side of the Tisza slid along a length of about 60 meters at Akolhát, downstream from the secondary dike at Kisköre (Nagy, 2004). Dike failure was imminent, but flood
fighters intervened rapidly and laid sandbags to construct supporting ribs and deterred the direct threat. (Figure 9) Had the levee breached at Akolhát, almost two meters of water could have been retained in a “basin” near the levee for a longer period of time. The basin itself was bordered by the secondary dike at Kisköre, the left bank levee of the Hany main canal and a newly constructed 80-meter-long dike built after the slope had slid. The height of the overflow used in the overflow formula would have been 1.5-2 meters lower, and would have allowed substantially smaller volume to spill.

Although the case presented above is not typical of classical localization, it is a good example of how the degree of inundation, overflow volume and damages can be reduced.

Occasionally, reducing the level of water on the water side is also possible, in case there is an upstream reservoir or an emergency reservoir in the vicinity is available. Two dike failures occurred on the left hand side of the River Túr among unique hydrological conditions during the Upper Tisza flood of 2001. Although the level of the water was decreasing in the river itself, volumes of water were retained in the reservoirs of the River Túr on the Romanian side upon Hungarian request, thereby reducing water level in the vicinity of the failure so as to prevent the breaches from widening and to allow blocking as soon as possible.

When historical data are not available, it is very difficult to estimate the height of overflow in case dikes failed in earlier years. We know that whenever a levee breach failed due to the mechanism of overtopping, water level had to rise above a certain height, i.e. the height of the contemporary dike prior to the beginning of the breach formation. But we are uncertain about the degree. The fact that the crest did not run parallel to flood level even in those days is another uncertainty, for instance because the different sections of unpacked levees compacted at different degrees under their own weight. We can also mark the contemporary crest stage
water level on the nearest water gauge but the density of water gauges in that period was too rare to allow for reliable interpolation. Remains the possibility of using the known stage to draw a line on the present-day longitudinal section running parallel to current design flood levels. That allows us to determine approximately the height, which is assumed to have been the level of water that year. It is at that level that the breach could have occurred and the water must have spilled across the opening. Even that way, we are off by 20-30 centimetres, because of disregarding that the gradient of the river was different than it is today. Another problem is our ignorance of the height of overflow at the time, which can only be specified relative to the present level of the terrain using the plotting procedure described above. We have no information whether the flood washed the levee away right down to the level of the terrain, it washed away more or less of it.

It only is possible to make this approximation for locations where the levee follows the same path as it used to, where the longitudinal profile of the levee is available and where there used to be a water gauge near the studied site. Only 74 of the 97 known long dike failures along the Tisza would have allowed such an approximation. In several cases we should have used water gauges placed at a distance of 30-40 kilometres before the establishment of the uniform Flood-warning System in 1892 for defining exact water levels, which would have been very inaccurate. Further inaccuracies would result from the reduction of the length of the river by 452 kilometres (37%) with 102 diversion cuts between 1846 and 1895, and the increased gradient of the river. Moreover, more than three quarters of the recorded dike failures along the River Tisza occurred in that period in Hungary. It is almost impossible to take into account the effect of those diversion cuts today. That is why no more than 11 levee breaches allowed the specification of overflow height with more or less accuracy relative to the present level of the terrain. Unfortunately these data are also loaded with additional errors as we have no information on the height of the “bar” which normally remains on the water side upon a levee failure, as discussed in Chapter 5. Data regarding the size of the weir crest fail to show up in historical records.

That is why our first reaction was to reject the study of the relationship between overflow height and the length of a levee breach regarding both the Tisza and other rivers, but later on we continued researching the River Tisza from this aspect recognizing that the definition of overflow height does not satisfy stringent technical requirements in full.

Using the methodology described above we estimated the head on crest of the overflow at the initial stage of the failure for levee breaches along the Tisza. These figures should be treated with caution because the accuracy of the overflow height may be at +/- 30 cm variance due inter alia to the aforementioned changes of the river (and to the fact that the high water gradient of the Tisza is less than 3 cm/km in certain locations, and more than 1 m/km in other locations).

Figure 10 points out no more than the tendency of the relationship between. As overflow height increases, so does the length of the levee breach but the correlation is sloppy in terms of both the power function and the exponential function (Figure 10). That is probably due to the multitude factors that are at play. All in all, the results do not contradict the physical law that raising the height of overflow will increase the boundary shear of the water which corresponds to the increase of the opening of a dike failure. The data show that the lower the height of the levee, the less variable the width of levee breaches will be.

---

4 Within the range of 10-15 km.
5 10% of the height of the levee.
The two points in the left hand side of Figure 10 indicate high ground\textsuperscript{6} overflows.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Dike failure length as a function of overflow height along the Tisza (above) and Danube Rivers}
\end{figure}

\textsuperscript{6} High ground or high bank was phrases used before the middle of the 20th century to describe elevations along a river which were not reached by floods before. At present high ground means a assigned line of protection that is higher than the design flood level (DFL) but lies lower than DFL+1 m and has no man made flood control structures.
5.4. Levee Size and the Geotechnical Properties of a Dike

The size of a levee and its geotechnical properties pose one of the most interesting questions beyond any doubt. Three factors should be considered here:
- the size of a levee;
- the material of a levee;
- the structure of a levee.

The effect of the size of a levee is difficult to determine due to two contradictory tendencies. Doubtlessly, a larger levee is expected to offer greater resistance. It is also true however that the size of the cross section of a levee is not set arbitrarily. The height of a dike relates in some way to the height of previous high waters. Larger dikes presuppose larger overflow heights and consequently faster water speeds and larger boundary shear, etc. On the other hand it is more difficult to wash away a levee and to widen the width of an opening if the section is large than if it is smaller. As time passes, some equilibrium state will inevitably be created. That depends on the parameters listed and will correspond a point at which a quasi rest state is reached in the widening of a levee breach. Even if levees with large cross sections are more favourable, dimensions normally fall victim to construction cost. Constructing levees with a larger cross section costs more. That is why constructing slopes at the inclination of 1:3 or flatter is not typical in quite a large number of countries.

The material of levee at the site where the opening section gets formed is also essential. Results of the analysis made on the role of soil types are summarized in Table 4 and Figure 11. The hazard of shifting particles, erosion and hence of increasing the length of a levee breach is higher with fine particulate soils that offer no cohesion than with clays and with gravel of rougher grain (N.B. the latter soils are rarely used for constructing homogeneous levees).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Data</th>
<th>Breach length (m)</th>
<th>Dike height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pcs</td>
<td>min</td>
<td>average</td>
</tr>
<tr>
<td>CH</td>
<td>4</td>
<td>66</td>
<td>96</td>
</tr>
<tr>
<td>SC</td>
<td>17</td>
<td>5</td>
<td>87</td>
</tr>
<tr>
<td>CS</td>
<td>10</td>
<td>22</td>
<td>107</td>
</tr>
<tr>
<td>MS</td>
<td>4</td>
<td>58</td>
<td>135</td>
</tr>
<tr>
<td>S, GS, MG</td>
<td>4</td>
<td>35</td>
<td>92</td>
</tr>
<tr>
<td>Total</td>
<td>39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 4: Final length of breach in case of different soil types and dike heights*

Fine particulate soils with no (or low) cohesion can be dislocated and washed away at lower speeds of water than highly cohesive soils. This effect is important at the edges of openings. Practical experience shows as mentioned earlier that a vertical wall of earth is normally formed at the edge of a levee breach by the levee stub (Photos 1-10). The water flowing by wears away the levee toe and the levee above will collapse and leave vertical wall yet again. The faster the flowing water can decompose the edge of a levee stub the faster this process is. If a levee stub is made of a soil that slower waters can also decompose, the width of a levee breach will be larger. Such soils include types that lend themselves to erosion, poorly compacted soils and disperse soils (Photo 25).
Relationship of height of the dike vs final length of breach in case of different soil types

(49 data)

Fig. 11. Relationship of height of the dike vs final breach length and different soil types
The Corps of Engineers came practically to the same notional conclusion from its Probable Non-Failure Point (PNF) test (1992). Using simple rules of geometry, they recommended reducing the cross section of levees with small cross sections to determine a specific probability of destruction. They required that slopes constructed from fine particulate non-cohesive soils should be of a ratio of 1:4 rather than 1:3, which is recommended for compacted soils. That is to say poorer quality soils posing erosion hazard have a smaller effective cross section.

The structure of a dike is also important. Good quality compacted earthworks offer greater resistance and the width of a bridge will reach equilibrium state along a shorter length because the structure will withstand the boundary shear of the water to a greater degree. Several examples of this have been found among the dike failures of the past two centuries, first of all at the locations listed in Table 3.

5.5. Factors Determining Outflow Volume

5.5.1 THE FLOW CONDITIONS OF THE RIVER RELATIVE TO THE SITE OF THE LEVEE BREACH

The flow conditions of a river, including the conditions of the water side bed and of the flood plain, can influence the length of a breach in the main. These factors, however, are only relevant after the initial formation of a breach, because almost every failure develops due to static water rather than the dynamism of the river. (The latter can occur along mountain stretches of torrent streams but that would require water velocities that erupt through a levee breach, v=3-4 m/s.)

5.5.2 TERRAIN CONDITIONS ON THE PROTECTED SIDE

The weediness of the flood plain, the width of the flood bed, the roughness of the path along which the water reaches the breach as it moves from the flood bed and terrain conditions may play a role in shaping the length of a breach. Smaller amounts of water will pass through a breach in dead space with much less boundary shear than the case when the mainstream of the high water directs the flow against a breach.

The terrain conditions of the protected side may reduce the volume of the spill or may form a barrier to the flow of the water. Elevating terrain, a natural (or man-made) “basin” or any obstacle that blocks free flow on the protected side will reduce the volume, the energy and the boundary shear of the spill.

The reason why the opening reached no more than 4 meters in a dike failure near a structure on the left hand side during the Fehér-Kőröös flood of 1995 was because less than 1 hectare was inundated due to the terrain conditions of the protected side and water filled that small pool in a few minutes (see Case Study Report submitted under D6.7 by H-EURAqua on Dike Breach Due to Hydraulic Structure Failure Along Fehér-Kőröös in late 1995). Also, the case of the breach of the right bank dike of the River Danube at Surány in 1991 has to be mentioned here as a similar example, where the plum-stone shape, 6 ha pool between the primary and secondary flood defences was filled rapidly, causing a 38 m long breach only (see Case Study Report submitted under D6.7 by H-EURAqua on The subsoil failure at Surány at the flood 1991).
5.5.3 THE DISCHARGE OF THE RIVER

The river discharge plays a major role. Doubtlessly, the higher the discharge of a river, the larger the volume of the spill can be, and the larger volume will carve a larger opening into the levee, with all other conditions being equal. This premise is justified by processing statistically the data of dike failures.

To get homogenous result dike failures were classified into four categories by river. The river with the largest discharge in Hungary is the Danube, its discharge among flood conditions upon entry into the country is about 10500 m$^3$/s, which drops to about a 8000 m$^3$/s with a value at 8600 m$^3$/s at Budapest. Discharge is higher than 13000 m$^3$/s were only measured downstream from the influx of the Száva and that of the Tisza before the Danube leaves the Carpathian Basin. The discharge of the Tisza during flood spreads much more evenly between 2700 and 4000 m$^3$/s along the section between levees.

The remaining rivers of Hungary fall into two other categories. The larger tributaries of the Danube and the Tisza, including the rivers Bodrog, Maros, etc. represent roughly identical order of magnitude in terms of discharge. The tributaries of the Hármas-Köröös, the rivers Rába and Szamos also belong here.

The fourth category groups the small rivers of Hungary with flood discharges inferior to 150-200 m$^3$/s. These are Tarna, Zagyva, Hernád, Zala, etc.

As mentioned above, the length of only 142 breaches of the 329 that have occurred along the River Tisza in the past 150 years are known. The problems arisen during data processing included:

- defining discharge value for several levee breaches in Hungary in the 19th century. Estimates were calculated using known discharges of subsequent floods.
- regarding certain breaches the total length of several breaches is known. These are shown as average length.
- the statistical processing of the data produced a very steep distribution curve from breach lengths. To facilitate easier processing a quasi normal data set was produced by eliminating the lack of symmetry.
- the length of most of the breaches in Table 3 was so big that they were eliminated from the data set after the homogeneity of the data was examined.

The average width of the breach of the 125 dike failures with known breach length from the total number of 397 levee failures along the Danube Hungarian section comes to 130 meters (Figure 12). The variation of the data taken from the left and right hand side differs, which is why the areas delineated at the top and the bottom of the output square in Figure 12 show an identical variance with the average.

Figures 13 and 14 show the average breach width for the four categories mentioned above on natural and logarithmic scale. It is clearly visible that rivers with larger discharges show the formation of larger levee breaches on average. If one can draw a conclusion from the four figures, one might say that the width of a levee breach grow with grow of the river discharge.
Fig. 12. Dike failure length as a function of discharge along the Tisza (above) and Danube Rivers.
**Fig. 13.** Dike failure length as a function of discharge

**Fig. 14.** Dike failure length as a function of discharge, logarithmic scale
5.6. The Role of Time

Time plays a relevant role from two perspectives:

- The time it takes to reach the full length of a breach, (90-95% of the final opening),
- The timing of the dike failure relative to flood culmination,
- Any alterations in the length of an opening during the decades that elapse?

Whilst the first aspect is determined by local circumstances, the second allow cumulative evaluation of all the influencing conditions.

We lack essential experience regarding how the width of a levee breach changes in time in the early stages of a developing failure. This is where the EU-financed IMPACT project and the dike failure tests performed in Norway try to come up with helpful information.

It is indisputable that it takes very little time, less than a day for the opening in most levee breaches to reach a stable width, which is not susceptible to major enlargement subsequently. The exact time that takes, however, is unknown in Hungary and no computer modelling or local large sample experiment will reveal what terminal length a breach will reach. That value would be important for specifying overflow volume, which is a necessary parameter in determining the expected size of the area to be inundated.

Another important aspect of the time factor (also covered by the data collected) involves the point of time at which a breach occurs relative to flood culmination. Obviously, a breach developing before flood crest is less favourable. Yet, this is only important in locations where maximum period a flood takes to move down is a couple of days. Floods along the Hungarian section of the Danube may last 50-70 days, or even 90 days in special cases. From this aspect the middle and lower sections of the Tisza are more disadvantageous, as flood duration may reach 90-120 days there. The flood of 1876, which moved along the then semi-regulated Tisza, lasted 163 days in Szeged, first of all because of the backwater effect of the Danube.

Using available data regarding the third role of time, we studied how the time of occurrence influenced the length of dike failures in Hungary over a longer period of time. Although both the river and the system of dykes have changed a lot in the past 200 years, we tried to perform an analysis on the river types determined in Chapter 5.2.

We have information of 329 dike failures that have occurred in the span of 150 years along the Tisza Hungarian section, including only 142 breaches with known length. Even that set includes many instances where we are only aware of the total length of several breaches. When processing these data statistically, these were considered at average length. The annual breakdown also shows annual breach length averages.

Our preliminary expectations suggested that the length of levee breaches would tend to diminish, because as time passed, earthworks became larger in cross section, were safer and of better quality. It is worth noting, however, that one could also explain the opposite trend with reference to the rising flood height, which bears down on levees with increasing load, hence water spills with greater power when a dike fails and the superior boundary shear creates wider openings.

The trend line plotted from annual breach length averages climbs slightly upwards in case of the Tisza and shows a steep decline for dike failures along the Danube (Figure 15). Very small rivers and tributaries demonstrate significant increases (Figure 16).
Fig. 15. Temporal trend of dike failure length along the rivers Danube (above) and Tisza (below)

\[
y = 183000 e^{0.004x} \\
R^2 = 0.072
\]
5.7. The role of the failure mechanism in the final length of the breaches

We made also an attempt to find the role of failure mechanism in the final length of the dike breaches along different rivers and tributaries. Results of this attempt can be seen on Figure 17 without any definite relationship.
Fig. 17. Role of failure mechanism in the final length of the dike breaches along different rivers and tributaries.
6. SCOUR PIT SHAPE

Hardly any information is available about the shape and surface of scour pits. A general assumption suggested that scour pits get formed on the dry side and hardly if ever find their way to the wet side. Data regarding scour pit depth are also scarce. Scour pits are surprisingly deep occasionally.

Scour pits are unquestionably formed by the drifting, shearing, erosive force of the water gushing across a failed dike. The overflow formula is quite convincing about the likelihood of flow velocities greater than 4-5 m/s developing when flood defences fail in Hungary. Scour pit development begins at the site where the hydraulic jump is developing as a result of the transition of supercritical flow to subcritical flow, somewhere near the dry side levee toe.

6.1. The Conditions of Scour Pit Formation

Practical experience suggests that the development of a scour pit depends on several factors, including first of all subsurface conditions, but it is also determined by the mechanism of dike destruction. Unranked by priority, the factors that contribute to scour pit formation are:
- the mechanism of dike failure (Chapter 5.3),
- the overflow height of spilling water, hence water velocity (Chapter 5.4),
- the geotechnical properties of the subsurface structures of the levee (Chapter 5.5),
- the role of time (Chapter 5.6),
- flood fighting activity (Chapter 6).

Although we are not yet capable of capturing the exact theoretical conditions of scour pit formation, practical experience allows us to make certain statements:
- The formation of scour pits is highly infrequent if the surface of the underlying soil is composed of hard and very cohesive (rich and medium) clay.
- Scour pit development coincides with certain mechanisms of dike destruction (boils, hydraulic failure of subsoil, flow across the subsoil of the dike).
- The development of scour pits is highly likely with grainy and transitional soils of low cohesion. Mention should be made of the propensity of these soils to give way to boil formation or hydraulic failure.
- The development of a scour pit also depends on time and the overflow height of spilling water. If water spills across a breach and falls over a high weir head for a long period, even superior quality sub-soils may get decomposed. Water spilling for shorter periods or over lower overflow heights has a smaller propensity to scour pits.

It is easy to understand the effect of the factors listed above, but it is also practical to offer some examples to illustrate the role they play.

6.2. Scour Pit Statistics

Statistical processing of historical dike breaches allows us to study the theoretical conditions of scour pit formation, and the justification of assumptions. One must be aware, however, that historical data are incomplete, and the more we go back in time, the scantier they become.

Of the more than 1241 levee breaches identified in the territory of Hungary, only 91 (~7%) cases offer more accurate information on the existence of a scour pit. In 56 (62%) of the 91 cases, a scour pit definitely existed, in 35 cases (~38%) we are perfectly sure of the contrary. Table 5 shows the distribution by river of reliable scour pit information, suggesting that:
Most of the data concern the Danube, making up 45% of all the information and 60% of the identified scour pits.

The reason for the limited availability of data about scour pit existence along the Tisza is that few levee breaches occurred in Hungary in the 20th century.

Most of the scour pit information indicated the coincidence of scour pits with breaches along the Danube and the Tisza, and the lack of such formations during dike breaches along smaller tributaries (Szamos, Rába, Berettyó, Marcal). Hence the data suggest that the likelihood of scour pit formation or our awareness of pits is greater along larger rivers.

<table>
<thead>
<tr>
<th>river</th>
<th>Scour pit</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>existed</td>
<td>Not ex.</td>
<td>Total</td>
</tr>
<tr>
<td>Danube</td>
<td>33</td>
<td>7</td>
<td>40</td>
</tr>
<tr>
<td>Tisza</td>
<td>5</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Tributeries</td>
<td>9</td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>Small rivers</td>
<td>9</td>
<td>17</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td>56</td>
<td>35</td>
<td>91</td>
</tr>
</tbody>
</table>

*Table 5. Distribution of scour pits by river*

A study of the dike failures of the past 200 years reveals the following historical records:

- The oldest dike breach in the Tisza valley with information confirming that a scour pit developed occurred at 50+541 tkm on the right bank of the Tisza in Bodrogköz in 1865. The contemporary description mentions a breach of 120 meters caused by an ice jam at the 45+600 tkm section near "Várma" lake at Tiszakarád (a monography of the Bodrogköz Flood Control Society, 1896), but no more information about the scour pit.

- Scour pits developed during the Danube River ice flood of 1876 at the two levee breaches directly upstream from the ice jam at Ercsi. The pits remained detectable in the 1990s (even though contemporary descriptions failed to mention them). It was through these breaches that water inundated Csepel Island and the territory of the Pest County Sárköz Flood Control Society (Moder, 1896), which had just been formed, and flowed a large distance to the town of Baja.

- Probably the most memorable levee breach in the territory of Hungary occurred along the right bank of the Tisza River in 1879. Known as the Petres breach, it culminated later on in the Szeged disaster (Károlyi, 1969), and also involved the formation of a scour pit. An encircling dam was constructed on the dry side to restore the safety of flood defences.

- There were two levee breaches in the territory of the Titel Tisza-Danube Embankment Maintenance Society in 1895: at 19+000 km and at 20+800 km on the right bank of the Tisza River in the Csurog-1 levee district at around midnight on April 11. Although the mechanism of the failure is unknown, the description by the society mentions the need to construct encircling dams to close off the openings because of the large scoured pits. (Titel Tisza-Danube Embankment Maintenance Society)

- Pits got scoured at each of the breaches along the right bank of the Danube River in Szigetköz in 1954 with the most likely cause being the mechanism of destruction and the existence of non-cohesive granular soil (Szepessy, 1983).

- The deepest known scour pit developed in the 18+627 tkm section on the right bank of the Danube River near Bogysisló in 1956. The bottom of the pit was 18.2 meters below the crest (or 15.5 m below ground level). The pit eroded back to the wet side and its depth reached 12 meters at a distance of 15 meters from the axis of the levee. The dike failed on
March 11 and restoration finished in June after carting 50000 m³ of earth to the site to fill 
the pit.

- The scour pit with the largest size is also associated with the flood of 1956. Piping led to 
the failure of the levee in the 39+750 tkm section between Dombori and Bogyiszló on 
March 10. More than 4 hectares of clay mixed sand soil was washed away. The breach 
expanded to 250 meters in length and the scour pit also found its way to the wet side. On 
the dry side, the deepest point of the pit reached 10.5 meters at a distance of 50 meters 
from the axis of the levee, 12 meters at the axis line and 9 meters below ground level at a 
distance of 25 meters from the axis of dike. 216 400 m³ of earth was used to fill the pit.

- The most accurate data regarding scour pits and the related soil conditions have survived 
about the dike breaches during the ice flood of 1956. (ÁBKSZ 1978)

- In 1980, the line of defense failed at the pumping station at Hosszufok on the right bank of 
Kottos-Körös (see Case Study Report submitted under D6.7 by H-EURAqua on The Körös 
Valley flood of 1980). The scour pit also spread to the wet side to a degree that contrary to 
common practice the sheet plank wall had to be built on the dry side (Report by a 
committee of experts, 1980). When the last sheet was hammered into position the 
difference between upstream and downstream water levels was still close to 50 cm.

- We have reliable information about the presence or lack of a scour pit in 72 cases (39%) 
out of the 183 dike failures that have occurred in Hungary over that past 60 years.

A statistical analysis of scour pit formation should look at both the time and circumstances of 
pit development as well as the reasons why one did not develop in certain cases.

We have information about the size of the scour pit in 22 (39%) and about the depth of the pit 
in 36 (62%) out of the 56 identified cases with scour pits (Table 6). The average depth of 
scour pits is 5.7 meters below ground level, their average size is 8260 m². Minimum and 
maximum values are indicated in Table 6. Based on information about 20 cases (36%), 
43 000 m³ of soil had to be moved to fill the pits on average.

<table>
<thead>
<tr>
<th>Scour pit</th>
<th>min.</th>
<th>average</th>
<th>max.</th>
<th>No. of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth m</td>
<td>0,4</td>
<td>5,7</td>
<td>15,0</td>
<td>36</td>
</tr>
<tr>
<td>Area m²</td>
<td>100</td>
<td>8260</td>
<td>40700</td>
<td>22</td>
</tr>
<tr>
<td>Volume m³</td>
<td>200</td>
<td>43600</td>
<td>216000</td>
<td>20</td>
</tr>
</tbody>
</table>

*Table 6. Typical scour pit properties*

Undoubtedly, data about scour pit size have survived whenever restoration incurred 
significant outlay of funds, that is to say that values identified for average size and average 
volume of soil needed for restoration are likely to be higher than what they would be if the 
dataset was larger.

We have knowledge of a total of 35 pits, about which information is available on their 
location in the cross section of the levee, including 8 cases (23%) where the scour pit occurred 
on the dry side only, 7 cases (20 %) where the scour pit was located under the dike crest and 5 
cases where the pit was located on the dry side and below the levee (Table 7). The fact that no 
scour pit occurred on exclusively on the wet side or on the wet side and under the levee 
inevitably means that scour pits develop under the levee on the dry side, i.e. the assumption 
regarding scour pit development proves to be correct (Table 7).

In 15 cases (43%) out of the 35 scour pits, where more information is available on cross 
section, the pit expanded to the wet side (Table 7), i.e. it occupied space on the dry side, under
the levee and on the wet side. In other words, there were no scour pits on the wet side unless they had grown by erosion to reach it from the dry side or from under the levee.

Table 7 shows the average depth of scour pits in the cross section based on the data associated with the formations discussed in the preceding paragraph. Although average depths do not vary significantly, it is surprising to see that scour pit depth on the wet side is almost identical to that on the protected side, and average depth is the largest below the crest.

<table>
<thead>
<tr>
<th>Scour pit</th>
<th>On the water side</th>
<th>Under the dike</th>
<th>On the protected side</th>
<th>Under all three places</th>
<th>Total</th>
<th>Average depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>on water side</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>6.3</td>
</tr>
<tr>
<td>under the dike</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>8</td>
<td>27</td>
<td>8.0</td>
</tr>
<tr>
<td>under protected side</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>23</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Table 7. The position of a scour pit in the cross section of the levee

Of the 91 dike failures, the length of 86 is known. The average length of dike breaches with scour pits is significantly larger (90 meters for 51 breaches), than those without a scour pit (58 meters for 35 breaches). These two figures suggest that regardless of other conditions scour pits form more easily if a breach is spacious, or the width of a breach grows in response to the turbulent flow associated with scour pits.

Most of the information available on scour pits date back to the period of 1945-78. A publication by ÁBKSZ\(^7\) (1978) helped a lot during data collection as it contains two important remarks about scour pits:
- A scour pit existed in 24 (30%) out of the 81 dike breaches under study.
- The development of a scour pit is unlikely if cohesive topsoil is at least 2.5 meters thick.

6.3. The Role of the Failure Mechanism in the Formation of Scour Pits

As mentioned above, certain mechanisms of destruction (boils, hydraulic fracturing of the subsoil, subsoil piping) are associated with the development of a scour pit. Statistical processing of historical data supports that view.

We have accurate information that a scour pit was associated with 91 dike breaches that occurred in the territory of Hungary. In two out of the 91 breaches two options were recorded as the mechanism of failure, so the calculation contains 93 items. In 11 out of the 93 cases (~12 %) the mechanism of destruction is unknown. Of the remaining 82 cases, 49 (60 %) was accompanied by scour pit development, while 33 (40 %) was not (Table 8).

The figures show that a scour pit got formed in each of the 20 cases when the dike failed due to hydraulic subsoil failure (Table 8), which justifies the hypothesis we made above (Chapter 6.1).

Except for the cases of overtopping, the remaining figures in Table 8 do not lend themselves to making significant statements due to the limited number of cases. When dikes were destroyed by overtopping, the number of times that a scour pit got formed equals the number of times one did not develop.

The 91 cases include 11 (~12%) instances without definite knowledge about the mechanism of dike destruction. In these cases the number of times a scour pit got formed is three times the number of times that one did not develop (Table 8).

\(^7\) Hungarian abbreviation of the Flood- and Drainage Emergency Organization
Table 8. The role of the failure mechanism in the formation of a scour pit

<table>
<thead>
<tr>
<th>Failure mechanism</th>
<th>No. of data</th>
<th>Scour pit existed</th>
<th>Scour pit not ex.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overtopping</td>
<td>52</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Subsoil failure</td>
<td>14</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>Deliberate cut</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wave erosion</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Construction</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Dike body</td>
<td>9</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Other known</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Not determined</td>
<td>11</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>93</td>
<td>57</td>
<td>36</td>
</tr>
</tbody>
</table>

6.4. The Overflow Height of Spilling Water

The overflow height of spilling water is one of the most important factors contributing to the formation of a scour pit. As mentioned above, dike breaches are “single-point” formations (occurring within a short section), and develop in two directions along the longitudinal axis of the levee. A scour pit is also formed at a “single point” only to expand in multiple directions horizontally and vertically. As time passes, equilibrium is reached; the scouring power of the water spilling across the breach is too little to enlarge the pit any more. With all other conditions given (such as subsoil stratification, soil types, the topography of the dike breach etc.), the overflow height of spilling water (hence water velocity) is the single factor that will shape and develop a scour pit. Time also plays an important role in that regard (Chapter 5.6). Scour pits are unquestionably formed by the drifting, shearing, erosive force of the water gushing across a failed dike. The overflow formula is quite convincing about the likelihood of flow velocities greater than 4-5 m/s developing when flood defences fail in Hungary. Scour pit development begins at the site where the hydraulic jump is developing as a result of the transition of supercritical flow to subcritical flow, i.e. somewhere near the levee toe on the dry side. The effect of the volume of the spill and river discharge can be neglected and is limited to whether or not the river can sustain the volume of water spilling across the breach.

Of the 91 dike breaches, there are 77 with identified levee height. Of the 77 cases 44 (57%) included a scour pit, and 33 (43%) did not have one. The ratio of average levee height is 3.1:2.9 (both meters), which suggests that the likelihood a scour pit developing is greater when dikes are higher than average due to the associated above average overflow height. Of the 82 cases with known failure mechanisms, 52 included overtopping. In 48 of theses cases the height of the levee is also known. There were 26 overtopping cases (50%) associated with a scour pit, and 26 cases (50%) that were not, including 22 (~85%) and 26 (100%) cases, respectively, with identified dike height. Mention must be made of the fact that in each of these 22 cases the dike was higher than average, whilst in the 26 cases belonging to the other set, the dike was lower than average. The ratio of average levee height is 2.9:2.5 (both meters), which also suggests that the likelihood a scour pit developing is greater when dikes are higher than average due to the associated above average overflow height.

6.5. The Geotechnical Properties of Scour Pit Formation

The geo-technical properties of the sub-soil in a flood defense line are beyond any doubt one of the most interesting issues relating to scour pit formation.
A publication by ÁBKSZ (1978) suggests that “the development of a scour pit is unlikely if cohesive topsoil is at least 2.5 meters thick.” This statement is inaccurate for a number of reasons:

- Both the Hungarian and several foreign standards classify silt and silty fine sand as cohesive soil types. One must assume that the authors of the publication did not have silty fine sand in mind when stipulating this idea about the resistance of cohesive soil to being washed away.
- Unfortunately, highly cohesive soil types can also be of loose structure or have intermittent transient or poorly cohesive micro layers, which will promote the decomposition of the surface.
- There is no point identifying 2.5 meters of thickness as a threshold value. Water will always decompose the surface and when it does so, it has “no idea” of the types of soil below a certain depth. And once water has worn away 1 meter of the surface, the scour pit will be 1 meter deep regardless of the thickness of the cohesive soil below.

Non-cohesive (or poorly cohesive soils) with fine particles can be washed away at lower water velocities than strongly cohesive soils. This effect is important from the perspective of scour pit formation. When a 4-meter high dike fails, mean water velocity can reach 5 m/s in the breach.

Unfortunately, geo-technical descriptions of the location of dike breaches tend to be extremely superficial. The available information does not include strata boundaries, strata descriptions nor soil properties. Table 9 shows the distribution of soil types at dike breaches from the perspective of scour pit formation.

Of the 56 dike breaches with a scour pit, there was information on the sub-soil of the failed dike in 31 cases. There are very few (11) cases where there is definite knowledge of the lack of a scour pit and sub-soil conditions are known. Table 9 suggests that the presence of sand mixed gravel, gravel mixed sand or gravel in the sub-soil under a dike breach always coincided with the formation of a scour pit. These cases are limited in number, because there were only 8. The presence of a scour pit was more frequent in silt mixed sand and sand mixed loam than its absence. Muddy soil types tended not to allow scour pit formation (Table 9).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Scour pit</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existed</td>
<td>Not ex.</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Dispersive clay</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Sandy clay</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Clayey sand</td>
<td>9</td>
<td>2</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Silty sand</td>
<td>9</td>
<td>1</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Gravely sand</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Sandy gravel</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>No data</td>
<td>25</td>
<td>24</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>56</td>
<td>35</td>
<td>91</td>
<td></td>
</tr>
</tbody>
</table>

*Table 9. Soil types identified in dike failures*

Erosive, poorly compacted and disperse soils pose a special problem. One can assume that sandy soil with a low coefficient of irregularity, clay susceptible to the development of cavities (Szepessy 1981, 1983), and loosened soils (by e.g. deep plowing) are washed away
more easily. The dike breach at Halaspuszta in 1980 demonstrates disperse clay from among
the aforementioned soil types (Photo 25).

In 53 cases of 111 (~48%), the sub-soil of the levee is unknown. Of these, one and a half
times as many had a scour pit than those without one (Table 9), suggesting that the
information retained regarding the sub-soil of dike breaches with scour pits is much less.

6.6. The Role of Time in Scour Pit Formation

Time plays a relevant role from several perspectives. The width of an opening will grow until
it reaches equilibrium state (Nagy, 2004a). the same is true about scour pits. As time passes,
the spill keeps increasing the size of the scour pit and then overflow height reduces as the
discharge of the river reduces or as the flood cell gets filled and the scour pit stops growing as
equilibrium is reached. The interval during which the spill flows across the opening is
important from this respect. There are three factors that limit the flow across the breach:
• the stability of the flood level of the river,
• the inundation of the protected area,
• and the actions of flood fighters aimed at closing the breach.

The duration of the flood level varies widely in Hungary from river to river or rather from
river section to river section. Depending on the size of the catchment area flooding takes half
a day to one to two days on the upstream section of smaller rivers. Flooding may last 50-70
days, or in special cases 90 days along the section of the Danube in Hungary. The middle and
lower sections of the Tisza are more unfavorable from this respect as flood duration may
reach 90-120 days there. The 1876 flood on the river the Tisza moved down along a more or
less regulated river and lasted 163 days in Szeged mainly due to the backwater effect of the
Danube.

The inundation of the protected area (the flood cell) depends on topographic conditions, the
size of the area and the discharge of the spill.

The actions of flood fighters also play a major role in the development of a scour pit. Strenuous and persistent flood fighting efforts may increase or reduce the width of a breach
and may reduce the quantity and duration of the spill. Photo 20 shows a tamed dike breach
along the Trianon levee on the Sebes-Körös river. When a breach is closed, the effect that
leads to scour pit formation ceases to exist. This factor is impossible to model during a study
of scour pit size.

One of the functions of time (which was also subject to the collection of dike failure data)
involves the time at which a dike fails as compared to the time of flood peak. Undoubtedly,
the most unfavorable situation involves a dike breach before the flood reaches its peak, but
that is only important at locations where the flood takes no more than a couple of days.

7. EMERGENCY ACTIONS AFTER DIKE FAILURE

The actions of flood fighters play a role in the development of the length of the breach. When
a dike breaches, the people on the spot must begin protecting and securing the levee stub as
soon as possible, as József Péchy wrote in the 19th century (Photo 6). Preventing the breach
from growing is the first step in closing a failed levee. Securing the levee stub early on can
come the levee breach from widening any further even before the equilibrium state is
reached. That is because securing the stub direct contact between the boundary shear of the
spilling water and the material of the levee can be avoided.
Attempts to fill the opening may follow. The technique to be adopted depends on local conditions. Flood fighting records taken in the Carpathian Basin during the second half of the 19th century captured several cases when the width of the breach was brought under control first, and – working extremely hard – the breach was closed off in one or two days. These interventions did not occur along torrent flows but rather in sections where high water levels last weeks.

Flood fighting activity also plays a role in the development of the length of a levee breach. Strenuous and persistent flood fighting efforts may reduce (or increase) the width of a breach. The history of Hungarian flood control in the Carpathian Basin has recorded several dike failures, where flood fighters exerted superhuman effort to close a breach among high water conditions (Photo 20). There is no way to capture this factor in a model or a numerical expression for a study of the length of levee breaches.

When the flood fighters closed the failed dike at Hosszúfok in 1980 (Photo 17) the difference between the level of the river and that of the inundation was almost 50 cm. Although that difference would not have altered the length of the opening substantially, the volume of the spill was reduced, which was critical for the successful defence of the confinement lines (see Case Study Report submitted under D6.7 by H-EURAqua on The Körös Valley flood of 1980). Had they not managed to close the levee breach at such an early stage, the case would still demonstrate clearly the effects of the activity of flood fighters.

If flood fighters are passive and their actions are limited to monitoring the events, local circumstances will determine the evolution of an equilibrium state when the opening on a levee will not expand any longer. In case of each of the dike failures we possessed something kind of data regarding the development of the breach length in time, just as in 2001, it took less than 24 hours8 to reach that stage.

During the flood of 2001 on the Upper Tisza, two dikes failed at a distance of about 800 meters along the Tisza in Hungarian territory. The conditions (levee height, levee cross section, sub-soil, river discharge, flood fighting activity, terrain conditions on the protected side, etc.) at the two breaches were fairly similar. As a result, the length of the breaches happened to be quite similar, and the equilibrium state was reached at 115 and 140 meters, respectively, and the opening failed to expand any longer thereafter.

In theory, a persistent flood on a river with high discharge may provoke breaches to extend over hundreds of meters if the protected side is capable of receiving so much water. To prevent levee breaches from widening and to reduce the rate of expansion, it was common practice in Hungary to mutilate levee stubs transversally in the 19th and early 20th centuries. The transverse cut-off of the stub changed flow conditions slightly, the degree of scouring under the levee stub was reduced, and a shorter length was sufficient for the width of the opening to stabilize.

Fighting floods, as mentioned above, may have adverse consequences in extending the length of a breach. During the Oder flood of 1997, helicopters dropped stone-packed bags down the middle of the breach before securing the levee stubs. As a result, the breach extended, or in other words, the equilibrium state, which had set in, was impaired.

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8 The width of the levee breach would in all probability have reached terminal width, but fighters were not busy doing something else rather than recording it.
With all other conditions equal (i.e. parameters such as sub-soil stratification and the topographic position of a dike breach) it will be the overflow height of the spill (and hence water velocity) that shapes and develops a scour pit. In this regard, the most important duty would involve the reduction of water velocity, which could bring the widening of the breach under control. The development of flood fighting techniques should bear this aspect in mind.

Scour pits may erode back to spread into the wet side (Photos 8, 17, 21, 22 and 25 and Figure 12). The dike breach at Hosszúfok during the 1980 flood on Kettős-Körös is an example of that (see Case Study Report submitted under D6.7 by H-EURAqua on The Körös Valley flood of 1980). The scour pit spread to the wet side of the levee, which is why the row of pile planks (constructed during the flood) had to be hammered into place along a large arch on the protected side (Photo 17).

As referred to above, practical experience suggests that a vertical wall of earth gets formed at the edge of a breach near the levee stub. The water gushing by eats into the levee toe and the structure above it collapses to leave a vertical wall yet again. The faster the flow can decompose the edge of the levee stub, the faster this process is. This experience was utilized by flood fighters in the 19th century to prevent dike breaches from widening or to slow down the expansion. A slope was cut into the vertical wall of earth at the levee stub, while protecting the stub that was formed that way. That method ensured reaching equilibrium state with a smaller opening, which increased the potential to close off the breach later on.

We have no flood fighting technique to defend ourselves against scour pit formation and no potential solution has yet been identified (however, number of preventive solutions exist to improve the foundation soil stability in case of dike sections identified as prone to hydraulic failure by geophysical methods supplemented by pillar borings).

8. DETERMINATION OF EXPECTED BREACH LOCATION

8.1. Location of Possible Breach of Flood Dikes due to Overtopping

Practically, the crest level of flood dikes is varying along the length of the dike. In the investigation of the height of dike crest, tendencies and occasional variances can be found. Since the planned height of the dike is to exceed the design flood level with a defined freeboard, tendency or trend in the height of the dike crest will be observed. Therefore the actual level of the crest of the dike can be related to the design flood or to the design crest level (which can of course to be related to a certain probability of the flood level). However, there are random variances of the crest level in comparison with the design level. The variances are partly the result of the achievable accuracy of the construction of earthworks, that of the differences in consolidation along the length of the dike and also that of the erosion in case of unpaved crest.

The longitudinal profiles of the dikes contained by the integrated contingency plans can serve with the results of the survey on the crest height (Fig. 18. – see on over next page). According to the rules applied in Hungary, dikes are subject to repeated geodetic check in every 5 years. Cross sections are measured in every 50 meter therefore between two measured cross section a lot of different (or equal) results can be obtained. On the other hand, reduction of the intervals between the measured cross sections becomes useless or unfeasible in a certain limit.
Fig. 18. Longitudinal profiles of a flood dike
Probability of water level belonging to the weakest chain (in respect of overtopping, to the lowest crest level) is equal with the probability of overtopping. However, total length of the sections having lowest crest level can only be defined by statistical analysis, resulting in the frequency of different crest heights, the average crest height and the standard deviation of the measured heights from the average (Fig. 19.).

In practice, along middle or lower course river sections, the dike sections having deficiencies in height can be defined and designated by the evaluation of the forecasted peaking water surface and the crest line of the dike on the longitudinal profile.

The necessary temporary heightening (sandbagging, mudboxing, etc.) can even be successfully done in case of only 18-24 hours lead-time. Along the flood embankments of the Upper-Tisza Regional Water Authority under such warning conditions temporary heightening in a length of about 30 km in 24 hours became a routine work between 1998 and 2001 (see also page 8 of “The March 2001 flood on Upper Tisza” in our D6.7. report).

There are also cases, when the temporary heightening can be successfully done in the overtopping water of even 20-30 cm depth (see page 8-9 of “The Kőröös Valley Flood of 1980” in our D6.7. report). Similar experience was gained during the flood of November 1998 along the Upper-Tisza, when a section of the dike on the left bank of the river at the village Milota was already overtopped but the defence activities were successful.

Experiences of the above cases confirm that not necessarily the “weakest chain” (the profile having the lowest crest height) will be the location of the dike breach. Depending on the available lead-time and the preparedness of the flood emergency organisation, as well as on the magnitude of the height deficiencies and the maintenance of the dike (existence of healthy and dense grass cover) emergency operations may fill the gap in due time.

In practice, it is very difficult to get prepared for the protection of dikes against overtopping along rivers of upper course type, where the forecast lead-time is very limited. On the other hand, the high velocity of the flash floods in the narrow river valleys threatens with scouring of the dikes and banks as well here.

For the cases of indefensible overtopping or if the countermeasures are in delay, on the expected the failure process the results of the large and small scale model tests of the

Fig. 19. Flood levels and crest heights as variables along the length of a dike section
IMPACT project, while on the expectable length of the breach our report in D6.6 can give the basis of considerations or calculations.

8.2. Location of Possible Breach due to Hydraulic Failure of the Foundation Soil

Undisturbed soil profile of alluvial floodplains in the Carpathian Basin consists generally of a cohesive or mildly cohesive Pleistocene alluvium, underlain rarely by a transition soil type, followed by layers of increasingly coarser granulometry. The layers vary in thickness and the transition between them is a continuous one. Layers of gravel or even coarse sand are confined to particular regions and depths, mainly along the Danube River, especially in the region between Bratislava and Győr, called Szigetköz on the Hungarian side and Žitný Ostrov in Slovakia.

Boils along flood embankments have been familiar for long as the concentrated emergence of underseepage discharge at the landside of the embankment. The water carries varying amounts of soil, deposited in the form of a cone around a crater, but this has not proved determinative in the majority of cases. Nevertheless, great efforts have invariably been made at checking these, since in some infrequent instances a duct under the embankment eroded and widened rapidly until the embankment body slumped eventually into the resulting cavity.

Danger of the development of hydraulic subsoil failure (sand boiling) is present along flood embankment sections, which have been built on an identifiable, special stratification of the foundation soil. According to our present knowledge, strata, consisting of a relatively thin, impervious covering layer, underneath of which a thin permeable layer of fine grains is deposited, can be considered as dangerous. Danger is growing if under the fine-grained layer a coarser layer of higher permeability is deposited, especially in case of irregular changes in strata depth. This type of three-layered strata is considered to be the most dangerous for the stability of the foundation soil of the dikes (see Fig. 20.).

8.2.2. The boiling process

8.2.2.1. Conventional or “slow” boiling

Structure and the process of a conventional piping/sand-boiling phenomenon are shown on Fig. 20.a. and b. The flood embankment is built upon a relatively thin impermeable covering layer, underneath of which a thin layer of fine sand can be found, and the undermost layer is a relatively thick aquifer consists of coarse sand, gravelly sand or sandy gravel.
In the covering layer, on the protected (land) side of the dike a channel formation starts for certain reason, as a consequence of a decayed root, or a hole of a field mouse, etc. The water flowing out concentrated has a relatively high velocity exceeding the critical gradient of the fine sand. There is an erosion process starting, transporting the fine sand and building a cone around the crater from the particles on the surface around the hole. As the sand is being washed out from under the covering layer, the length of the channel is growing towards the Riverside. The channel growing under the dike reduces the stability of the covering layer and that of the dike itself, leading to sliding of the landside slope or to subsidence of the levee, causing levee breach.

However, it is very important that in this process the amount of water that transports the fine sand originates from seepage process. Furthermore, the critical gradient of the fine sand is $I = 0.8 - 1.0$, but the value of $\Delta H/L$ along the levees is round $1/8 - 1/12$. Therefore the initial gradient of the piping phenomenon can only be considered as $H_s/d$, its value may reach or exceed the critical gradient easily, and thus the process of erosion may start. As the channel, consequently its surface is growing, the velocity of water will decrease since the amount and the discharge of water originating from seepage will not increase considerably. This is the reason why theoretical studies and considerations have implied that large cavities under the embankment are unlikely to result from boil ducts eroding backwards slowly according to the familiar, above mentioned hypothesis.

Nevertheless, conventional or “slow” piping/boiling is always a subject to control and fight against because there is no any guarantee against a dangerous degeneration of the phenomenon. Controlling is rather possible; usually there is considerable lead time for the countermeasures shown in Fig. 21 after their first observation. Since boils are dangerous as long as they carry particles as the result of erosion, the counterpressure basins have to be only heightened until pure water is flowing out. The water flowing out of the basin should be collected and drained away to avoid saturation and softening of the base of the dike.
8.2.2.2. Rapid piping/boiling

There were several levee breaches in the past decades also in Hungary and in some of our neighbouring countries caused by hydraulic failure of the foundation soil of the dike, where and when there was no chance to intervene due to the very fast process that occurred.

Levee breach in 1954 at Ásványráró, right bank of the Danube, was witnessed by chance a very experienced hydraulic engineer, Mr. L. Marek. He was standing on the crest of the dike watching the landside slope when suddenly, about 5 m away from the toe densely muddy water erupted in a diameter of about 1m! Only in a few seconds cone of depression was observed in the flood water and the dike collapsed in some minutes.

There is no exact or detailed description on the dike breach occurred on the left bank of the Danube at Čičov in Slovakia in 1965. The personnel of guards reported about a sudden and huge eruption of muddy and sandy water near the land side toe of the dike. As a consequence of this and the following rupture, about 800 million m³ water inundated huge territories in Slovakia.

Similar levee breach was observed on the left bank of the Danube during the Great Flood of 1965 at Bačka Palanka in Yugoslavia. “Never trust a woman or a flood embankment” – said Ing. Dusan Zdravković, responsible section manager after the event.

Our D6.7. report on extreme flood events in Hungary contains the description of the Körös valley flood of 1980, where details on the breach at Hoszúfok are given. This failure happened at 6.35 a.m. on July 28, 1980, before the very eyes of two guards going towards the later breach site and about from a 100 m distance they observed a sudden and very strong eruption of water on the protected side. The water was reported “black and densely muddy”. The dike broke through in some five minutes. The width of the breach increased rapidly, at 7.00 a.m. it reached 10 m, the final width was as much as 78 m.

According to all known description, eruption of water was explosion-like and sudden, and the following dike failures were very fast. No descriptions read about preliminary boils carrying water and particles building cone around the crater.

Potential explanation for these "high-rate" boils is that the soil cover on the landward side is burst at a weak point by the upward pressure acting on it, whereupon the fine-sand layer situated below it becomes liquefied (fluidized) almost instantly by the ensuing surge wave along the full length of the duct. This explanation is in closer agreement with the processes and phenomena actually observed than the former, although neither this could be supported by experimental evidence. A considerable advantage of this theory consists, however, of the possibility of predicting analytically the pressure, which triggers the phenomenon by causing the cover to burst.

Fig. 22 is illustrating this process, where there is no initial slot or hole in the covering layer that could reduce somewhat the uplift pressure and no erosion channel develops. The covering layer under pressure breaks suddenly due to pressure conditions shown by piezometric pressure-line “1”. The equilibrium would be reached with the pressure line “3” if there would be enough time to release the water from the fine sand layer. Since the support of the covering layer is lost in a second, the loss of pressure transforms the piezometric line as shown by pressure line “2” and the underlying saturated, usually loose fine sand layer gets liquefied in its whole length. Pressure wave of the breaking up of the covering layer contributes to breaking of the cover layer on the waterside as well (or, as in case of the Hoszúfok example the sand layer is in direct communication with the mean bed), the liquefied layer is being washed out under the dike, and finally it leads to the collapsing of the dike.
8.2.3. Identification flood embankment sections prone to hydraulic failure

As it has already been mentioned under 8.2.1., precondition of the development of this dangerous phenomenon is the existence of the three-layered stratification within a relatively shorter section differing from the stratification from the neighbouring sections. The question to be raised is, where the probability of such stratification is the highest?

Investigations performed after the remarkable big dike breaches proved that such anomalies in the stratification are to be expected, and all the mentioned hydraulic failures occurred at those singular points where the track of the dike intersected ancient river beds, which had been disconnected and silted up several hundred or possibly several thousand years ago.

Prior to river regulation and embankment construction the rivers meandered in braided channels across the flat lowlands in Hungary, changing their course continuously. The flood embankments were therefore necessarily built across alive, or abandoned, silted-up beds. In case of the first case we can assume that crossing of alive meanders was made with careful preliminary dredging of silt, using change of soil as necessary, therefore there is no real cause not to trust in the performance of these crossings. Absolutely different is the evaluation of those cases where the track of the dikes crosses the ancient and silted up riverbed, identification of those is still difficult on the terrain nowadays.

An investigation programme resulted in the report entitled "Study on the paleohydrography, stratigraphy and morpho-genetics of the rivers in Hungary" was completed in the early eighties and presents welcome information prior to actual exploration about the potential soil conditions under the embankments. The study on the thousand-year shifts in river courses
included a methodology based on aerial photography, topographic maps and flood experiences for the identification and classification of meander crossings.

Ancient riverbeds are identifiable even in simple black and white (BW) aerial photographs. Aerial photos in the scale of 1:8,000 to 1:30,000 made in early spring, when the vegetation is still low, especially if they are made in the period of spring floods show contrasting shade along ancient course of silted up rivers. The tone of the ancient riverbed can either be darker or lighter than that of the neighbouring parts of the terrain. Darker tone indicates higher degree of moisture, while the lighter implies on higher degree of salinity or degradation of the covering layer along the bank of the ancient riverbed. Two basic cases we can face during the interpretation and evaluation of the aerial photos:

− There is at least 0.5-1.0 m deep depression in the track of the ancient riverbed. In such cases the ancient riverbed is observable by stereoscope (or directly in case of ortophoto) as a negative profile. Differing vegetation (reed, wed, shrubs) can also be observed.
− The ancient riverbed has been silted up totally or almost totally, it cannot be observed by stereoscopic techniques, only the difference in tone or in vegetation indicates their existence.

Investigation of these traces should be compared to micro-relief conditions and vegetation showed by detailed topographical maps. Phenomena observed during floods such as seepage on the protected terrain may help in identifying the intersections of dikes and ancient riverbeds. Fig. 23. and 24. shows examples of identified ancient riverbeds and their intersection with dikes. The latter is the case that caused the dike breach at Hosszüfok. Fig. 25. illustrates the formation of the three-layered dangerous strata on the concave bank of the ancient bed.

![Fig. 23. Ancient riverbed system along the Sebes-Körös River](image-url)
8.2.4. Classification of intersections of dikes with ancient dead riverbeds

Investigations and explorations proved that strata prone to hydraulic failures could definitely be observed at the intersections of dikes and ancient riverbeds. However, the stratification can differ depending on the following factors.

*Morphological position of the intersection along the ancient riverbed.* Usually at the concave bank of the river bend there is always a rather thin fine grained layer with inter-depositions of mildly impermeable layers deposited on thick coarse layers, covered by relatively thin impermeable layers (see Fig. 25.). Therefore from the viewpoint of the morphology of the ancient riverbed, the most dangerous strata can be found on the concave bank; thus an intersection of the dike with a concave bank of an ancient riverbed can be considered dangerous. Increased is the danger if the intersection falls to intertwining bends originating from different ages (see Fig. 24.), since both the starting and closing section of the given dike stretch falls to concave bends, as a result of which in the full length of the intersection variable thin fine-grained layers are expected to be found with thin covering layer.
Distance between the spot of infiltration and the intersection of dike with ancient riverbed. First of all the bank of the mean bed (or side branch closer to the given dike section than the mean bed itself) is to be considered as spot of infiltration, however, in case of wide floodway even a borrow pit opened near the dike, especially if penetrates into permeable layers can also have the same role.

The morphological characteristics of the mean riverbed near the intersection of the dike with ancient riverbed. In case near the intersection the mean riverbed has a convex bend, specially in case of slumping bank, decreasing of the infiltration distance, lack of colmatation can be expected, therefore such a shape of the riverbed is considered to be a factor increasing the danger. Infexion in the river morphology means also danger due to its possible migration, but is less dangerous than the previous one.

Summarising: particular characteristics that must be considered are
- the shape of the explored ancient bed in the intersection (intertwining of two ancient beds, convex or concave, inflexion, straight)
- the distance of the intersection from the mean riverbed (or from the borrow pit)
- the shape of the mean bed in the vicinity of the intersection (convex or concave bank, inflexion, straight)

Ranking of intersections is proposed by using a scoring system as follows:

<table>
<thead>
<tr>
<th>According to the morphology of the ancient riverbed at the intersection</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intertwining double crossing with concave banks</td>
<td>5</td>
</tr>
<tr>
<td>Intersection on concave bank or in inflexion</td>
<td>4</td>
</tr>
<tr>
<td>Intersection on convex bank</td>
<td>3</td>
</tr>
<tr>
<td>Intersection on straight section</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>According to the distance of infiltration</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between the bank of the mean bed (side branch, borrow pit) from the dike</td>
<td></td>
</tr>
<tr>
<td>0 – 30 m</td>
<td>5</td>
</tr>
<tr>
<td>30 – 50 m</td>
<td>4</td>
</tr>
<tr>
<td>50 – 80 m</td>
<td>3</td>
</tr>
<tr>
<td>80 – 100 m</td>
<td>2</td>
</tr>
<tr>
<td>over 100 m</td>
<td>1</td>
</tr>
</tbody>
</table>

The identified track of the ancient riverbed, the track of the flood embankment and that of the river has to be investigated on the layout. Intersection starting and ending sections along the flood embankment should be evaluated according to the above table (2*2 scorings) finally the morphology of the mean riverbed near the intersection has also to be scored as shown in the below table.

<table>
<thead>
<tr>
<th>According to the morphology of the mean riverbed at the intersection</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>convex bank</td>
<td>5</td>
</tr>
<tr>
<td>inflexion</td>
<td>4</td>
</tr>
<tr>
<td>straight section</td>
<td>3</td>
</tr>
<tr>
<td>Concave bank</td>
<td>2</td>
</tr>
<tr>
<td>Borrow pit</td>
<td>1</td>
</tr>
</tbody>
</table>
Final classification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Danger category I</td>
<td>20 – 25</td>
</tr>
<tr>
<td>Danger category II</td>
<td>15 – 20</td>
</tr>
<tr>
<td>Danger category III</td>
<td>10 – 15</td>
</tr>
<tr>
<td>Danger category IV</td>
<td>6 – 10</td>
</tr>
<tr>
<td>Danger category V</td>
<td>4-5</td>
</tr>
</tbody>
</table>

The least stable soil stratification should be anticipated at crossings belonging to Group I. The number of crossings in the hazard groups I, II III and IV was found to be 446, 978, 1286 and 264, respectively, representing a total of 2994, or 1.4 per kilometre in Hungary.

This classification was used to prioritise the detailed investigation of the intersections of dikes with ancient riverbeds. Investigation was made by geophysical methods (especially by horizontal geoelectric probing) supplemented by pillar borings to identify physical parameters of the soil types explored. An example is shown on Photo 19.

Studies on piping failures have revealed the importance of the density of the permeable sand layer under the embankment as regards stability. There are several indications, such as the minor amounts of material eroded by widely scattered small boils, that this sand layer becomes loosened successively under repeated flood exposures which is liable to lead to the loss of stability of the embankment and the structures crossing it. Further research into this very important problem is warranted.

After the passage of the 1991 flood wave the breach at Surany was explored. The boreholes sunk into undisturbed soil in the vicinity of the breach struck rd. one-half metre below the terrain surface a 1.5-1.7 m thick poorly graded sand layer of 1.31-1.46 g/cm³ dry density and uniformity coefficient $U = 2.5-3.3$. According to the official report a "high-rate" boil was the cause of failure.

Similarly, in the Hosszúfok case along the Kettős-Körös River in 1980, the presence of the badly graduated ($U \leq 3$), loose ($e = 0.79$) fine sand layer was decisive factor to the fate of the dike.

9. RESTORATION OF BREACHES AND SCOUR PITS

It is unquestionable that we only have information about scour pit size whenever restoration incurred significant expense. The cost of restoring a scour pit may reach 8-10 times the expenditure required to rebuild a levee.

The method selected for restoring a dike will depend on topographic conditions, the proximity of the river, ownership conditions as well as the presence (shape and depth) of a scour pit. Speed is a first priority in at least temporarily closing the breaches of failed dikes, especially along flashy streams. Final restoration of failed dikes can take place as soon as all the conditions are appropriate for constructing earthworks.

Most recently sheet piles have been used to close of breaches temporarily. Sheet piles are fixed at the levee toe on the wet side, unless local conditions require otherwise. Photo 11 shows how sheet pile type Cs-2 was used at the wet side toe to close off the emergency reservoir at Szeghalom in 1970.
When a dike fails without a scour pit, the job involves simple dike construction. The only extra jobs involved are the removal of soaked sections, and foundation work may begin. In the presence of a scour pit there are two possible methods to choose from:

- **Building a bypassing levee towards the wet side or the dry side.** Bypassing levees of this kind were constructed on the right bank of the Danube to restore the breach at Dombori in 1956 (Photos 21, 22, 23 and 24),
- A bypassing levee was built on the dry side to restore the breach at Petres, which culminated in the disaster of inundating Szeged in 1879. In that case the scour pit expanded to the wet side (Figure 26).
- Wet side bypassing levees are worth using in locations where the scour pit does not expand heavily into the wet side, the river is not near and constructing on the wet side does not reduce discharge cross section substantially.

![Figure 26. The location and restoration of the failed dike at Petres](image)

There are several good ways to restore dikes along the original path. If there is clay soil of proper quality in the facility, one can find out rather complicated cross sections. However, if there is a pit, water should be removed first and the pit should be filled with earth. Filling earth to remove water is no solution. The displacement of water from a scour pit by filling it results in a mess of soaked and non-compacted earth piling up in the pit, which equals creating a new hazard.

The dike breach near Tiszabökény (Bobove, Transcarpathia, Ukraine, 2001) was restored by bulldozing earth into a scour pit to displace water from it after the flood in 1998. Although, the water in the pit could have been drained by gravity due to the vicinity of the river and the steep bank (Photo 8), muddy topsoil from the neighboring plow field was bulldozed into the pit. (A few years later inevitable flood phenomena will be observed, and “miraculously” the levee will subside.)

Although, there have been several examples of repeated dike breaches at the same location during consecutive floods in the history of flood fighting in Hungary, no written evidence has yet been found of their relationship with the presence as well as to the restoration of former scour pits.

It is also important to restore the edge of a scour pit. Where earthwork meets natural soil formations at the edge of a scour pit, finely detailed earthwork is needed rather than mechanized mass movement of earth (see Photo 26.). At such locations, the deficiencies of restoration may trigger flood phenomena later on. A case of this kind happened during the restoration of the dike breach at Tivadar, which occurred late at night on December 31, 1947 (Nagy, 1999).
9.1. Improvement of the stability of the foundation soil

The locations of intersections of dikes and ancient riverbeds can be identified and strengthening thereof can be planned and designed in advance.

Since the major cause of damage to the dikes in these cross sections is liquefaction of the sand layers, counterbalancing or decreasing the head to the foundation soil either by limitation of infiltration or lowering of the seepage contours by draining can be considered.

Combination of these countermeasures, as can be seen in Fig. 27. is recommended.

![Fig. 27. Schemes of improvement of the stability of the foundation soil](image)

10. A STUDY OF CZECH DATA

The analysis of data collected in the Czech Republic followed the same principles, and allows the following statements to be made:

- The Czech partner has collected data about 40 dike breaches that have occurred along the Odra River and its tributaries since the flood of 1960 (cf. Case Study for breach parameters - Data collection sheet - Odra River catchment) Table 10 shows the distribution of Czech breaches by river.

<table>
<thead>
<tr>
<th>River</th>
<th>pieces</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lubina</td>
<td>1</td>
<td>2.3</td>
</tr>
<tr>
<td>Odra</td>
<td>20</td>
<td>46.5</td>
</tr>
<tr>
<td>Olse</td>
<td>7</td>
<td>16.3</td>
</tr>
<tr>
<td>Opava</td>
<td>6</td>
<td>14.0</td>
</tr>
<tr>
<td>Ostravice</td>
<td>9</td>
<td>20.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>43</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

*Table 10. Distribution of Czech dike failures by river*
Table 11 shows the annual distribution of Czech breaches. The flood of 1996 inflicted great damage on the catchment area of the Odra River.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Piece</th>
<th>per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>July</td>
<td>1</td>
<td>2,3</td>
</tr>
<tr>
<td>1965</td>
<td>Jun</td>
<td>1</td>
<td>2,3</td>
</tr>
<tr>
<td>1977</td>
<td>August</td>
<td>1</td>
<td>2,3</td>
</tr>
<tr>
<td>1985</td>
<td>August</td>
<td>1</td>
<td>2,3</td>
</tr>
<tr>
<td>1997</td>
<td>July</td>
<td>36</td>
<td>83,7</td>
</tr>
<tr>
<td>2002</td>
<td>December</td>
<td>2</td>
<td>4,7</td>
</tr>
<tr>
<td>2003</td>
<td>September</td>
<td>1</td>
<td>2,3</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>43</td>
<td>100,0</td>
</tr>
</tbody>
</table>

*Table 11. Annual distribution of Czech dike failures*

The total length of Czech levee breaches adds up to 2,757 meter based on 39 breaches. Average length comes to 70.7 meter (with the two extremes at 5 m and 400 m).

No trend could be plotted for the whole length of the river due to the relatively limited amount of information.

No temporal trend could be defined due to the relatively limited amount of information.

A total of 60 mechanisms of destruction were identified for the 33 breaches in the Czech Republic, with the distribution summarized in Table 12 and graphically represented in the pie chart in Figure 28. The most frequent mechanisms involved overtopping and wave erosion.

<table>
<thead>
<tr>
<th>Failure mechanism category</th>
<th>piece</th>
</tr>
</thead>
<tbody>
<tr>
<td>overtopping</td>
<td>15</td>
</tr>
<tr>
<td>stability loss of embankment due to seepage dike body</td>
<td>5</td>
</tr>
<tr>
<td>stability loss of embankment due to seepage at the base</td>
<td>2</td>
</tr>
<tr>
<td>stability loss of embankment due to leakage dike body</td>
<td>4</td>
</tr>
<tr>
<td>stability loss of embankment due to leakage at the base</td>
<td>2</td>
</tr>
<tr>
<td>stability loss of embankment saturation</td>
<td>2</td>
</tr>
<tr>
<td>wave erosion</td>
<td>13</td>
</tr>
<tr>
<td>scouring from water side</td>
<td>1</td>
</tr>
<tr>
<td>structure failure</td>
<td>1</td>
</tr>
<tr>
<td>deliberate cut</td>
<td>4</td>
</tr>
<tr>
<td>stability loss of foundation due to sandboil (piping)</td>
<td>3</td>
</tr>
<tr>
<td>stability loss of foundation due to sandboil (piping)</td>
<td>1</td>
</tr>
<tr>
<td>stability loss of foundation due to liquefaction</td>
<td>0</td>
</tr>
<tr>
<td>stability loss of foundation due to hydraulic failure</td>
<td>2</td>
</tr>
<tr>
<td>other</td>
<td>5</td>
</tr>
<tr>
<td>not well identified</td>
<td>0</td>
</tr>
<tr>
<td>total</td>
<td>60</td>
</tr>
</tbody>
</table>

*Table 12. Distribution of Czech dike failures by mechanism of destruction*

45 reasons of failure were identified for the 43 breaches in the Czech Republic, with the distribution summarized in Table 13. About 1/3 of the causes involves bad material and another third blames bad construction.
• We have 9 figures concerning the overflow height of spilling water for the breaches in the Czech Republic, including a few breaches with large initial width, but as the flood cell was filled up, the bottom of the opening did not reach ground level. Relying on the scanty data, Fig 29 suggests that the lower the overflow height, the wider the opening would be.

• Discharge varied between 150-2100 m$^3$/s on the rivers we analyzed. The data taken from 43 breaches in the Czech Republic are compiled in Figure 30 to show that the width of the breach dropped as water discharge increased. This relationship is just as impossible to evaluate as the relationship between the length of breaches and the size of the inundated area, which is based on 13 values and is shown in Figure 31. Evidently, some of the breaches had large initial width but the opening did not deepen much as the flood cell filled up.

![Mechanism of dike failure Czech data](image)

**Fig. 28. Distribution of Czech dike failures by mechanism of destruction**

<table>
<thead>
<tr>
<th>Cause of breach category</th>
<th>piece</th>
</tr>
</thead>
<tbody>
<tr>
<td>bad material</td>
<td>13</td>
</tr>
<tr>
<td>bad design</td>
<td>4</td>
</tr>
<tr>
<td>bad construction</td>
<td>15</td>
</tr>
<tr>
<td>bad maintenance</td>
<td>6</td>
</tr>
<tr>
<td>lack of appropriate emergency operation</td>
<td>2</td>
</tr>
<tr>
<td>no information</td>
<td>5</td>
</tr>
<tr>
<td>total</td>
<td>45</td>
</tr>
</tbody>
</table>

*Table 13. Distribution of Czech dike failures by reason for failure*
Fig. 29. The length of Czech dike failures based on overflow height data reported by Czech sources

Fig. 30. Relationship between dike failure length and river discharge based on data reported by Czech sources
Except for two cases, levee dimensions were identified for each dike breach in the Czech Republic. Fundamentally, the breaches occurred in dikes with steep slopes and small cross sections. Crest width was 2.5-3.0 meters in more than 50% of the cases.

- There were 10 values about sub-soil and 6 values concerning the levee as far as the geotechnical properties of failed Czech dikes are concerned. Statistical evaluation was impossible due to the relatively limited availability of data.
- There were only three scour-pits formed during dike breaches in the Czech Republic and no analysis was done due to scanty data.

11. SUMMARY

Experts from various countries studied and evaluated the shape, size and development of dike breaches as part of the IMPACT project. The processing of historical data complements large scale and small-scale physical tests and computer modeling appropriately.

Flood fighting activities in preceding centuries and systematic research have produced a collection of 1245 historical data regarding dike failures in Hungary. Despite the gaps in and the frequent errors of historical data, the high number of dike breaches facilitates statistical processing and the evaluation of the results allows us to draw interesting conclusions and lessons for future generations, for instance regarding the length of levee breaches. The effect of human intervention is easy to trace in the system of flood control on the basis of the changing number and length of levee breaches.

The expected length of a levee breach depends on a number of interrelated factors, yet there used to be no method for value estimation. The present studies allow us to declare that a starting point has been created for increasing the accuracy of expected breach length.
estimates. More than 1000 historical data have been processed to calculate the average breach length in the dikes of the Danube, the Tisza, their tributaries and the smaller rivers of Hungary. Neither breach length results, nor the temporal trend of breaches contradict the laws of physics.

Although quite a few factors, such as the geotechnical properties of levees, the flow conditions of rivers relative to the location of a dike failure, the effect of protected side terrain conditions are difficult to express numerically, whilst in the case of other factors, such as the activity of flood fighters, numerical expression was impossible, statistical processing offered results which were easy to interpret regarding a river or a river type. The analyses performed allow us to make technically sound estimates of expected breach length along certain rivers or river sections and the estimates can be used in localization calculations.

A study of the shape of dike breaches should take scour pit formation and the bar into account. An analysis of historical data shows that information on scour pits existed in 87 out of a total of 156 dike failure cases that occurred after 1945, a date since more accurate records have been kept. The 87 references to a scour pit include 51 cases (59%) where a dike breach actually developed (which corresponds to 33% of the breaches after 1945). One might therefore conclude that a scour pit is formed in one third of the dike failure cases. Based on our awareness of scour pit development we may assume that ratios are used to be similar in earlier times. Older literature and data on scour pit formation are extremely incomplete. In Hungary, Kvassay (1900, 1913) and Zawadowski (1891), who describe the largest number of dike breaches in the second half of the 19th century, only mention the development or the absence of scour pits in a few instances.

Although, scour pit formation does not increase the damages done by a dike breach very much as the damage done to protected values is normally orders of magnitude higher than the cost of reconstructing a dike, the statistical processing of historical data has provided useful experience and has enriched our technical knowledge. Flood controllers are likely to have more collected information on a scour pit development in the future.

Scour pit formation includes a lot of uncertainties, several factors, such as the actions of flood fighters are difficult to express in mathematical terms. Nevertheless statistical processing led to unquestionable results in certain areas as historical data managed to prove several former assumptions, word of mouth hypotheses regarding scour pits, such as the relationship between a pit and sub-soil conditions and the connection between scour pits and destruction mechanisms. The studies seem to indicate that the shape and size of a scour pit influences the size of a dike breach and must therefore be included in the models.

Evaluation of the results of the analyses

First conclusion is that observation and data of real failures of flood dikes cannot be compared to those of experiments. Observation on the formation and progress of the breach process fails in the significant majority of the cases, especially along smaller rivers, only the ‘result’ can be seen, not the process. The breach along the Danube right bank at Surány on the Szentendrei Island in 1991 happened in the night, without any previous sign, the guards checked the sight some one hour earlier. It is very rare that a process leading to dike breach can be observed by anyone, especially by professionals.

Even in case of a phenomena threatening with failure, all efforts are concentrated on defence interventions and in case of breach all efforts are concentrated on the preparation of possibly fastest closure of the breach, on evacuation, on the confinement (localisation of inundation)
etc., not on observation, measurements, data collection. Therefore observation concerning for example the water levels on the protected side starts always with considerable delay (placement of temporary gauges needs time and the same vehicles which are engaged in flood fighting, localisation and evacuation). In fact, such observations or measurements do not take place in every case of dike failures.

Factors affecting breach formation and location:
- we provided data in our interim report on the shapes of the breaches, including the occurrence of scour pit in different soil types and their size, on the remaining levee stubs, on the final length of the breaches.
- relations between the length of the breaches and the height of overflow, the flow rate of the river and the location of the breach along the river could be described. We found also relation between length of breaches and calendar years of occurrence (the role of time).
- role of other factors (size, geotechnical properties, river flow conditions and patterns, topographic conditions on the protected side, activity of flood fighters) are also discussed in our final report.

Results for the Industry
We do believe that the above results give very important data for the industry in their preparatory and emergency management activities. Furthermore:
- To assess potential location of possible breach of flood dikes due to overtopping is possible.
- Methodology to assess potential location of possible breach due to hydraulic failure of the foundation soil in alluvial river valleys is described.
- Relations described between the lengths of the breaches vs the height of overflow; the flow rate of the river and the location of the breach along the river may be a substantial support in planning and implementing confinement activities, and such data or relations are not provided by any of the work packages of the project.

Indicators of performance of the dikes can hardly be derived from breach data since the majority of breaches were caused by overtopping. Indicators of performance of a flood embankment can be derived from the resistance calculated from the geometry and geotechnical parameters of the dike and that of the foundation layers compared with the loads (and the probability of those), thus stability or failure probability of dikes can be calculated, and earthen embankments to withstand certain load can be dimensioned. The reverse process, to derive performance indicators from breach parameters is rather difficult due to high scale inhomogeneity of earthen structures.

However, with the utilisation of the geophysical methods, selection of dike sections deviating from those in the neighbourhood and posing problems during flood events can be done and the reinforcement of these ‘weakest chains’ can properly be done.

As far as the Hungarian experience is concerned, we use different geophysical techniques, especially multi-electrode horizontal geoelectric probing to investigate the subsoil conditions of the earthen embankments, and properly laid patterns of electrodes and software for producing ‘tomography’ of the dike body. Operational application of the methodology, even during floods is part of supervision system since more than ten years in Hungary.
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