LESSONS FROM HISTORICAL DIKE BREACHES IN THE CARPATHIAN-BASIN

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ABSTRACT. - Lessons from historical dike breaches in the Carpathian- Basin. The uniqueness of the topological features of Hungary (93000 km^2) in the Carpathian-Basin (~450000km^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 dikes 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 breach length. (Nagy 2000, 2001, 2004, 2006) More than nine years of historical research has identified over 2200 dike breaches, including 1054 case where the length of the breach is known.

Key-words: flood hazards, lessons, Carpathian-basin

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. Danube is drainage the Carpathian-basin, largest tributary is river Tisza on the east part of the basin.

In Hungary - situated in the deepest part of the Carpathian-basin - flood plains make up 22,8 per cent (21248 km^2) 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 2000 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.

The first evidences of local flood embankment construction date back to medieval times. Construction work on local flood embankments was started again along the Danube, the River Tisza and their tributaries towards the end of the 18th and early in the 19th centuries. In 1840 the total length of flood embankments in Hungary was 792 km, of which 464 km were in the Danube valley and 328 in the Tisza valley. This initial period of flood defenses development lasted to 1846.

The growing market for cereals in Western Europe, the recurring inundations and especially the 1845 flood on the River Tisza have prompted the landowners to join their forces in flood defence associations. Large-scale river regulation and parallel the flood dike construction projects extending to entire flood plain sections were thus launched in 1846. The first 11 km long embankment section was built on the initiative of Count István Széchenyi according to the designs of the engineer Pál Vásárhelyi along the cut through the meander at Tiszadob.

2. Statistics of past failures

The use of failure statistics to estimate the probability of dike failures presumes that

- the circumstances underwent no changes during the decades, centuries elapsed, and
- true data are available on the past events.

Data collection is a laborious, slow process. Even the data of events later than 1945 are difficult to trace and identify. According to a survey report of 1993, the floods between 1945 and 1993 have caused 84 failures (Nagy, 1993). The causes thereof were grouped as follows

- Overtopping: 59 (52 during the 1956 ice-jam flood on the Danube),
- Hydraulic soil failure: 13,
- Embankment saturation, loss of stability: 10,
- Leakage along structures: 2
- Unidentified positively: 8.

The statement that information could be collected on 84 failures would have been more appropriate. Research on historical sources of information always involves the possibility of discovering new data not included in previous reviews. In the present case the data of some dike failures on minor Hungarian rivers had emerged after the previous report was published (Nagy, 1996). The floods during the past 55 years have thus caused 140 dike failures, grouped as:

- Overtopping: 83 (52 of which during the 1956 ice-jam flood on the Danube),

- Hydraulic soil failure: 23,
- Embankment saturation, loss of stability: 10
- Leakage along structures: 2
- Other identified: 11
- Unidentified positively: 14.

The total obtained is 143 instead of 140, which is explained by the fact that in three cases different mechanisms of failure were named, which could not be judged as to their correctness. Evidently, the completeness of the list cannot be guaranteed.

Owing to the often-conflicting records, the collection of historical data on dike failures is a time-consuming task requiring close attention. Over the past 200 years over 2200 embankment failures have been reported in the Carpathian-Basin. The data on most of these are incomplete in the source documents. The failures are divided between the countries in the Carpathian-Basin shows Table 1.

Table 1. Dike failures in the Carpathian-Basin

Country	Dike failures (%)
Hungary	62
Romania	21
Serbia	6
Slovakia	9
Ukraine	2

3. The philosophy of data collection

The sources were reviewed with the aim of finding the following data on dike failures (Nagy, 2000): Year; iver name at the failure; Failure mechanism; Location (river, bank, stationing); rigin of the flood causing failure; Length of breech; vertopping without failure; Size of area inundated; Losses according to contemporary assessment; Number of casualties; Exact time of failure; Existence of a scour pit; The floodplain section affected; Other circumstances, notes.

The data collected were processed taking the following considerations into account (Nagy, 2000, 2004, 2006):

- The data were tabulated in the sequence: Year, River, Flood plain section
- In the data collection the Carpathian-Basin comprises the Dévény - Iron Gates Danube section and her tributaries
- Relatively little information is available on the flood on the River Maros in the 20th century, on the Dráva and Száva rivers, further on the floods after 1920 beyond the present boundaries. For more information on these co-operation with the neighboring countries is necessary.

- The time of failure had to be estimated often from the shape of the flood level hydrograph
- The failure mechanism was classified into the following eight groups: overtopping ydraulic soil failure eliberate cutting
  wave scour crossing structure oss of stability
  other known nidentified
- 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.
- The group of "crossing structure" contains the failures related to deteriorated culverts, etc. and leakage in their surroundings

4. Some interesting results

The list compiled is probably an incomplete one. Nevertheless, some conclusions of potential interest not only to professionals can already be arrived at there from:

- A unique attempt has been launched at reviewing the history of flood dike failures in a hydrographic unit shared by several countries.
- The number of failures surpasses all former expectations.
- The collection of this type of historical data is a time-consuming and laborious task.
- 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 data collection table.
- The data tend to become more ambiguous with time, though, unfortunately, the records on failures during the last three dates are also far from perfect.
- From the total number of failures for the present territory of Hungary is 1174. The number of failures per five-year periods demonstrates clearly that the large-scale flood control project launched in 1845 was not fully successful up to the turn of the century (Figure 1).
- Early in the 19^{th} century isolated areas were protected by dikes 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 dikes.
- Over 100 failures occurred annually during a few disastrous years in the second half of the 19^{th} century. The majority of these was caused by the large floods on the River Tisza in 1876, 1881 and 1888 (Nagy, 2000, 2004, 2006).
- In the second half of the 19^{th} century only three years were found thus far in which no dike failure was registered (1852, 1863, 1898).

- Most of the failures (375) occurred in the Körös Valley, where a total of 82 were recorded in 1879.
- The largest number of failures, over 200, was recorded in 1888 and in 1876.

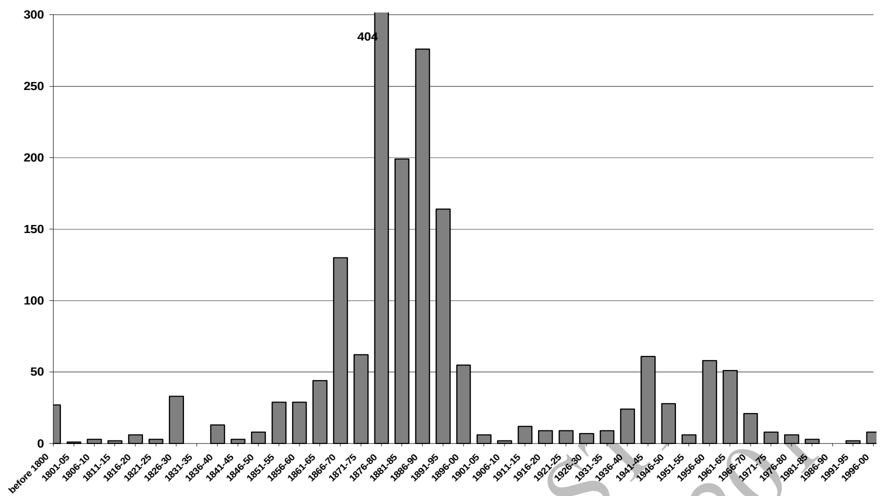

Figure 1. Five years distribution of dike failures

Failures were especially numerous along the Tisza tributaries at their emergence from the mountain reaches onto the plains.

- Along the Fekete-Körös 132 failures occurred between 1868 and 1887, 36 in 1869, 35 in 1879, 11 in 1881 and 11 in 1887,
- The right-hand dike along the River Szamos failed on 205 occasions during the 32 years between 1864 and 1896, e.g. at 49 points in 1881 and at 31 in 1888.
- The left-hand dike along the River Szamos failed on 75 occasions between 1864 and 1896, e.g. at 18 points in 1881 and at 9 in 1888.
- In the Tisza Valley 74 failures were registered up to 1850. From 1851 to 1900 The Tisza dikes failed on 150 occasions. High banks (considered safe) were overtopped 35 times.
- Of the 16 failures along the Tisza between 1901 and 1950, only 10 were on the present territory of Hungary.
- Along the Körös and Berettyó rivers 85 failures occurred in 1879.

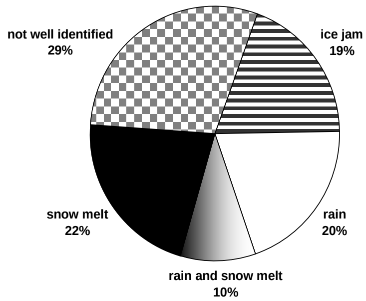

Figure 2. Distribution of flood origin

In the Carpathian-Basin high level water cause three thing, ice jam on the plain section of river Danube, heavy rainfall on the smaller rivers and on the upper sections of larger rivers, and snowmelt in spring. The largest floods become when the snowmelt appear with a heavy rainfall. The distribution of the flood origin can see on the Figure 2 (Nagy, 2000).
The failure mechanism is known in 525 cases, that is 29% of the total (Nagy, 2000) The distribution of those known is illustrated in Figure 3.

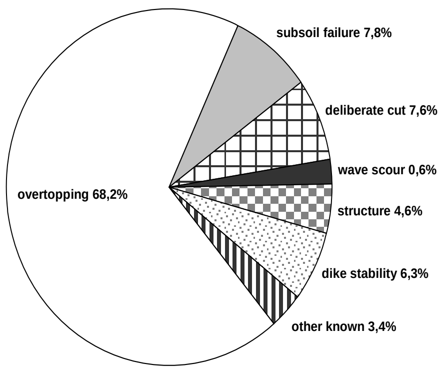

Figure 3. Distribution of failure mechanism

The term subsoil, or hydraulic soil failure was coined in the 20th century in connection with flood dikes, so that its application to earlier incidents is a retrospective interpretation.

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.

The calm period following the turn of the century was interrupted by the failures in 1942, 1945, 1954 and finally by the 58 during the Ice-jam flood on the Danube in 1956.

5. Dike breach length

A study of dike failures should first of all differentiate between dikes or dikes 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.

Photo 1. Dike Breach in England November 2000.

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 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 dike 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 the shape and depth of openings as they form upon dike failures to see what happens under natural conditions during the first thirty minutes of a dike breach. The project studies dike failures using on site large sample tests, small sample laboratory tests on a scale of 1:10 and computer modeling.

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

Practical experience suggests that dike 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,

G - the dimensions and geotechnical properties of the dike,

R - river flow conditions vis-a-vis the location of the breach,
S - topographic conditions on the protected side,
Q - the discharge of the river,
A - the activity of flood fighters,
T- the function of time.

Photo 2. Dike breach at Oder river left bank at Frankfurt am Oder in 23 June 1997.

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 dike breach. Although it is easy to comprehend the effect of the factors listed above, their role deserves illustration a through a few practical examples.

6. The shape of dike breaches

Dike breaches have typical shape. A study of the photographs taken of dike failures that occurred in recent decades reveals several similarities in the shape of dike breaches. (Photos 1 and 2)

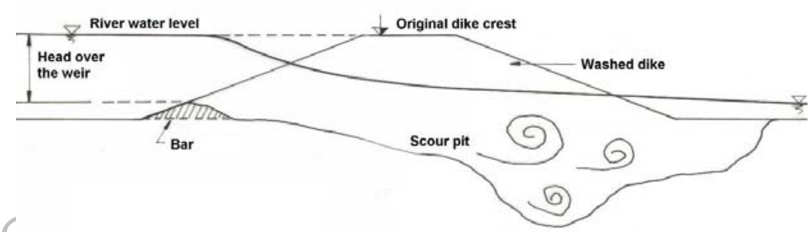

Figure 4. Typical cross section of a dike failure.

The remaining dike stubs are almost always vertical. Their direction is either perpendicular to the longitudinal axis of the dike or the opening narrows towards the protected side at a slight degree of inclination. (Photos 3, 4 and 5)

Photo 3. Elba river left bank at Dorctersen in 3. January 1976 (Germany).

A study of dike breach cross sections shows that water washes the full section of the dike away in almost every case. Nevertheless, a small piece of earth normally remains at the water side dike toe, and it reduces the height of overflow as the water falls over it. (Figure 4) This piece of earth is frequently called bar and bar height may even surpass 40 cm. This height reduces the height of overflow and the turbulence building up behind it helps scour pits develop.

Scour pit development depends on subsurface conditions, and will also be determined by the mechanism of dike destruction.

Photo 4. Kettős-Körös flood in 1980 Hosszúfok dike breach (Hungary)

Photo 5. Breach at Tisza right bank in 2001 (Hungary)

If the subsoil is composed of hard and rich clay reaching several meters in thickness, the formation of scour pits is highly infrequent, as opposed to grainy and transitional soils where the development of scour pits is highly likely. Such soils also lend themselves to the formation of boils, hydraulic sub-soil fracturing, which will inevitably culminate in scour pitting. Probably the largest scour pit in the Carpathian-Basin developed on the left bank of the Danube near Szeremle during the ice flood of 1956. The horizontal size of the scour pit was 157×250 meters.

Scour pitting also depends on the duration of time and the height of the overflow. 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.

Scour pits would rarely erode backwards to show up on the water side. The Hosszúfok dike failure during the Kettős-Körös flood in 1980 illustrates this phenomenon, which subsequent studies proved to have evolved due to the presence of disperse soil. The scour pit advanced to reach the water side of the dike, which is why the pile-plank barrier constructed during the flood to close the breach had to follow an unusual large curve on the protected side. (Photo 9) Photo 10 of the dike failure on the left bank of the Tisza at Királyháza in the Ukraine in 1998 also shows a scour pit that progressed to reach the water side.

7. The length of dike breaches along the rivers

The longest dikes breaches (> 300 m) that occurred in the Carpathian-Basin were

- in the 19th century, when dikes were very much inferior in size,
- along a river with high discharge (failures along the River Vág were situated in a section affected by the Danube), i.e. there were large volumes of water for replenishment,
- inundated spacious food areas, i.e. large volumes of water could spill across the breaches.

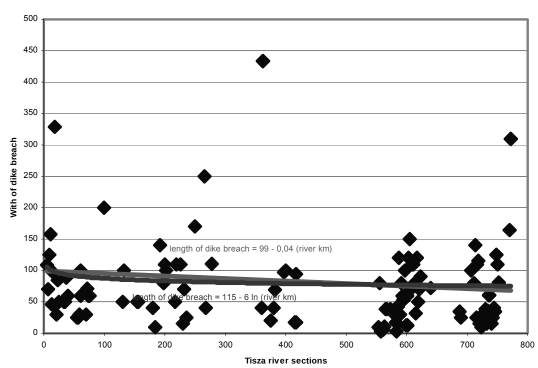

Figure 5. Length of dikefailures distributed by the rofiling of the River Tisza

Of the 329 dike failures along the 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.

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 dikes along 800 kilometers practically downstream from Huszt.

Figure 5 presents the length of dike failures distributed by the profiling of the River Tisza. The length of dike breaches along the Upper Tisza is not at significant variance with downstream data, nevertheless the curve of both the linear and the exponential trend climbs slightly upwards as the river approaches the recipient Danube, but the increase is not significant. The exponential curve reflects the effect of the embouchure into the Danube, but mention must be made of the fact that the backwater effect of the Danube is longer.

8. Factors determining outflow volume

8.1. The overflow height of spilling water

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 4, 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.

Overflow height may be reduced by constructing a stilling basin on the protected side. (Nagy 2004) Occasionally, reducing the level of water on the water side is also possible. Two dike failures occurred on the left hand side of the 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 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 when dikes failed in earlier years. We know that whenever a dike 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. 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 dikes compacted at different degrees under their own weight. We can also mark the contemporary crest stage water level on the nearest water gauge and use that level to draw a line on the present-day longitudinal section running parallel to current design flood levels. That allows us to determine 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 centimeters, 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 dike 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 dike follows the same path as it used to, where the longitudinal profile of the dike is available and where there used to be a water gauge near the studied site[1]. Only 99 of the 142 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 kilometers 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 kilometers (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. It is almost impossible to take into account the effect of those diversion cuts today. That is why no more than 12 dike 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 laden with additional errors as we have no information on the height of the "bar" which normally remains on the water side upon a dike failure, as discussed in Section 3. 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 dike 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 dike breaches along the Tisza (Figure 6). These figures should be treated with caution because the accuracy of the overflow height may be at +/- 30 cm variance[2] with actual fact due *inter alia* to the

[1] Within the range of 10-15 km.
[2] 10% of the height of the dike.

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).

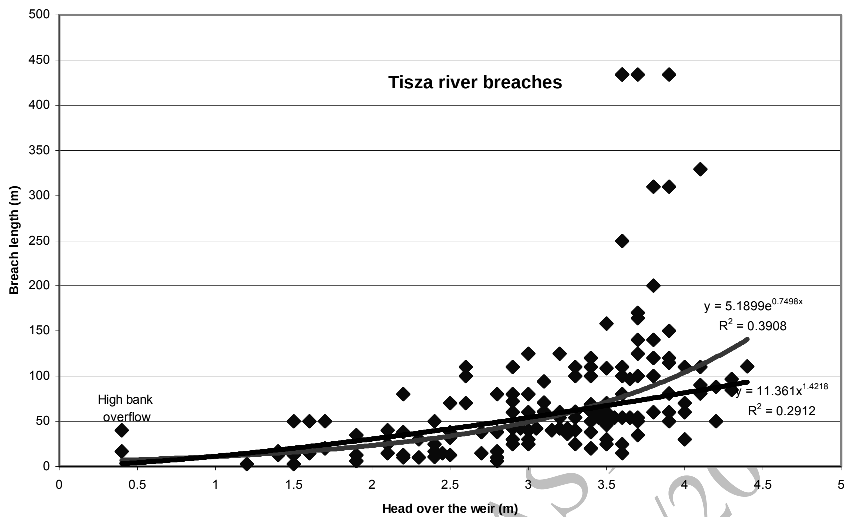

Figure 6. Head over the weir and the length of a dike breach

Figure 6 points out no more than the tendency of the relationship between. As overflow height increases, so does the length of the dike breach but the correlation is sloppy in terms of both the power function and the exponential function (Figure 6). 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 dike, the less variable the width of dike breaches will be.

The two points in the left hand side of Figure 6 indicate high ground[3] overflows.

[3] High ground or high bank, were phrases used before the middle of the 20^{th} century to describe elevations along a river which were not reached by floods before. At present high ground means an 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.

8.2. Dike size and the geotechnical properties of the dike

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

Photo 9. Dike breach at Korolevo in 1998 November (Ukraine)

The effect of the size of a dike is difficult to determine due to two contradicting tendencies. Doubtlessly, a larger dike is expected to offer greater resistance. It is also true however that the size of the cross section of a dike 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 dike 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 dike breach. Even if dikes with large cross sections are more favorable, dimensions normally fall victim to construction cost. Constructing dikes 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 dike at the site where the opening section gets formed is also essential. The hazard of shifting particles, erosion and hence of increasing the length of a dike 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 dikes.)

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 that a vertical wall of earth is normally formed at the edge of a dike breach by the dike stub

The water flowing by wears away the dike toe and the dike above will collapse and leave vertical wall yet again. The faster the flowing water can decompose the edge of a dike stub the faster this process is. If a dike stub is made of a soil that slower waters can also decompose, the width of a dike breach will be larger. Such soils include types that lend themselves to erosion, poorly compacted soils and disperse soils.

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 had been found among the dike failures of the past two centuries.

8.3. The flow conditions of the river relative to the site of the dike 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 dike breach, v=3-4 m/s.)

8.4. Terrain conditions on the protected side

The width of the flood plain, the distance of the flood bed, the coarseness 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 an opening. 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-Körös 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.

8.5. 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 dike, with all other conditions being equal. This premise is justified by processing statistically the data of dike failures.

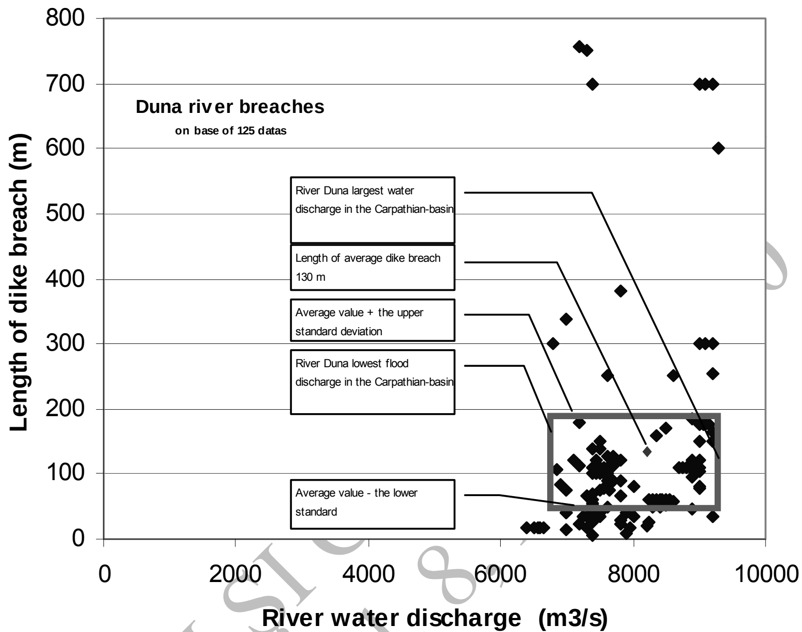

Figure 7. Length of dike breaches at river Duna

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 dikes.

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

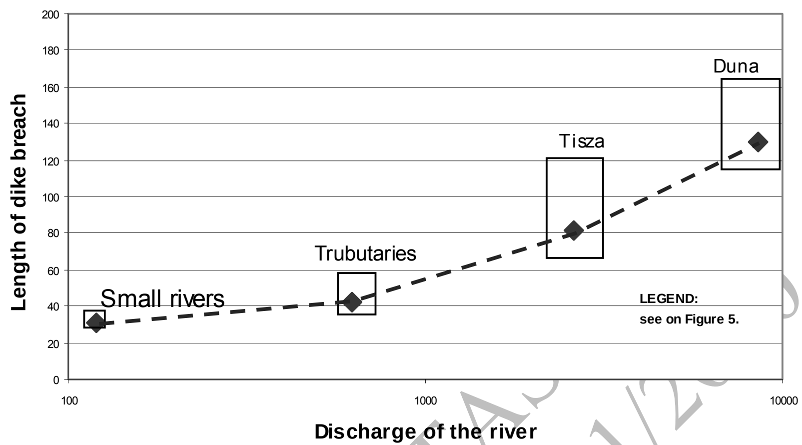

Figure 8. The average breach width for the four categories mentioned above on logarithmic scale.

The fourth category groups the small rivers of the Carpathian-Basin 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 of data processing included:

- defining discharge value for several dike breaches in the Carpathian-Basin in the 19^{th} century. Estimates were calculated using known discharges of subsequent floods.
- regarding certain breaches the total length of several breaches is known. These are shown at 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 long breaches 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 dike failures along the Danube comes to 130 meters (Figure 7). 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 7 show and identical variance with the average.

Figures 8 and 9 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 dike breaches on average. If one can draw a conclusion from four figures, one might say that the width of a dike breach grow with grow of the river discharge.

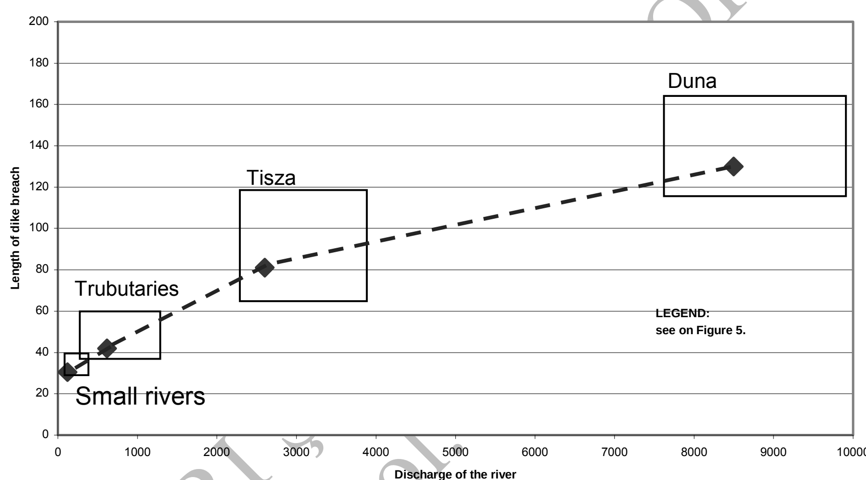

Figure 9. The average breach width for the four categories mentioned above on natural scale.

8.6. Flood fighting activity

Flood fighting activity also plays a role in the development of the length of a dike breach. Strenuous and persistent flood fighting efforts may increase or reduce the width of a breach. The history of Hungarian flood control in the Carpathian-Basin has recorded several dike failures (see Table 2), where flood fighters exerted superhuman effort to close a breach among high water conditions (Photo 11). There is no way to capture this factor in a model or a numerical expression for a study of the length of dike breaches.

The activity of flood fighters in the late 19th century is even more surprising when one is confronted with the fact that the dike failures in 2001 caught water management unprepared, and no attempt was made to block the breaches despite claiming much more sophisticated technical means than a hundred years ago. It is needless to say that the political and financial return on the cost of blocking a dike breach will be a hundred-fold or even a thousand-fold.

When the flood fighters closed the failed dike at Hosszúfok in 1980 the difference between the level of the water upstream and downstream was almost 50 cm. Although that difference would not have altered the length of the opening substantially, the volume of the spill was reduced. Had they not managed to close the dike breach at such an early stage, the case would still demonstrate clearly the effects of the activity of flood fighters, just as all the other examples listed in Table 2.

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 dike will not expand any longer. In 2001, it took less than 24 hours[4] to reach that stage.

During that flood on the Upper Tisza, two dikes failed at a distance of about 800 meters along the Tisza in Hungarian territory. The conditions (dike height, dike 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 120 meters, respectively, and the opening failed to expand any longer thereafter.

When a dike fails, the human resource on site must start protecting the stubs immediately. Preventing the breach from growing is the first step in closing a failed dike. Attempts to fill the opening may follow. The technique to be adopted depend on local conditions.

Securing the dike stub early on can help prevent the dike 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 dike can be avoided.

[4] The width of the dike breach would in all probability have reached terminal width, but fighters were not busy doing something else rather than recording it.

Table 2. Closure of dike breaches under flood conditions

Year	Place	Description	Source
1860	Tisza left bank at Tiszakeszi	The small breach closed immediately. No information about the applied technology.	Kvassay
1860	Tisza right bank	Between 97+500-98+300 sections, not far from Nagykörű at "Hidas" creek, closed less than one day.	Kvassay
1881	Tisza left bank, between Szentes And Mindszent	The temporary heightened part of the dike failed, but the soldier working on site closed immediately with driven sticks and local parasitics.	Péch
1883	Duna, at Monostor-szeg	First stopped the growing of the breach larger than 15 meter, and with 8 days hard work closed the breach when the water level difference was 0,5 m on the two side of the dike. Used wood piles and sandbags.	Péch
1886	Bega canal left bank at 16+800 km section	The new river regulation works reduced the cross section and caused higher water level on the upstream. The breach closed on the following day.	Kvassay, Zawadowski
1887	Béga left bank,	Between 24-25 km sections, closed on the same day.	Kvassay
1890	Duna left bank at Dunaszekcső	When closed the 65 m long 5 m deep breach the weir was nearly 0,5 meter.	Moder
1890	Duna, Kopolya dike	Through the 40 m long dike breach flowed the water out from the river. The weir head was nearly 4 meter. Used osier cylinder baskets and osier weaving mattresses. When the breach closed the upper water level was 1,2 m higher than on the other side.	Péch
1895	Béga right bank at 39 km section	Had been closed in the first two hours, before it become larger.	Kvassay
1895	At the mouth of Kutas canal	At Szeghalom city. Before the flood the inflow of Kutas creek to river Berettyó closed with a temporary dike, but it failed. The breach closed quickly, so the flooded area was only 330 ha.	Korbély
1909	Váli-víz	At Malonta puszta, on the territory of Ercsi-Iváncsa Association. The largest length of the breach was larger than 5 meters.	Kvassay
1940	Algyő main canal	The breach closed by pioneers driven wood piles into the ground. The length of the breach was shorter than 10 m, the water level difference was larger than 2 meters.	Trummer
1940	Sebes-Körös at Trianon dike	Used wood piles to close the breach, which length was sorter than 10 meters.	Trummer

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 dike breaches from widening and to reduce the rate of expansion, it was common practice in Hungary to mutilate dike 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 dike 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 dike stubs. As a result, the breach extended, or in other words, the equilibrium state, which had set in, was impaired.

9. 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 dike 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 dike 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 modeling 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 favorable. 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 the Carpathian-Basin 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.

We have information of 331 dike failures that have occurred in the span of 200 years along the Tisza, including only 149 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 shws annual breach length averages.

Our preliminary expectations suggested that the length of dike 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 dikes with increasing load, hence water spills with greater power when a dike fails and the superior boundary shear creates wider openings.

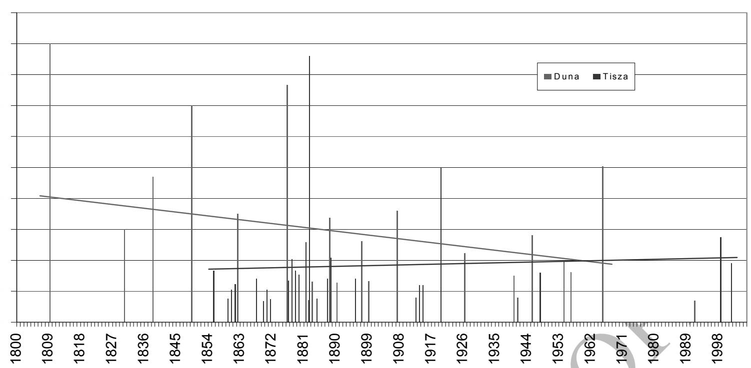

Figure 10. Length of dike breaches at Duna and Tisza rivers

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 10). Very small rivers and tributaries, however, demonstrate significant increases. (Figure 11)

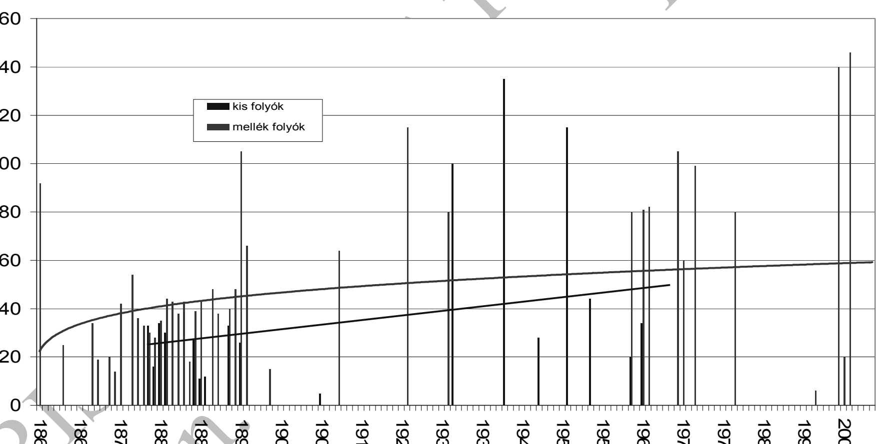

Figure 11. Length of dike breach at small rivers and tributaries

10. Summary

Owing to the continuous efforts at raising and strengthening the flood dikes in Hungary, the failure thereof has become rare in recent times. A review of the historical records may offer welcome help in the analysis of such rare events. The data thereon must be examined critically in the light of the contemporary conditions. It should be noted that the historical data are often inaccurate, but the role of such inaccuracies is likely to diminish, as the database becomes wider.

The data available for estimating the probability of failure are often scarce and in such cases rough estimation must be resorted to. Historical data on dike failures may offer valuable help in this respect.

Of the over 2200 dike failures registered during the past 200 years in the Carpathian-Basin, close to 1200 have occurred on the present territory of Hungary. Collection of the data on past dike failures has been started several years ago and will be continued as long as a reasonably complete database can be composed.

The main conclusions arrived at from the statistics of past dike failures are summarized as follows:

- As the result methodical improvements on the flood defences, the number of dike failures has dropped drastically in the 20th century;
- The diminishing number of failures implies that flood control in Hungary has attained a fairly high level, though not all hazards have been eliminated yet;
- The proportion of failures caused by overtopping has decreased and reveals a diminishing trend;
- The likelihood of failures caused by overtopping, however small, is confined presently to streams carrying a small flow (the probability thereof being practically nil along the Danube and Tisza rivers);
- The probability of failures associated with the subsoil (boils and hydraulic soil failure) is liable to grow;
- Owing to the growing number of structures (e.g. gated culverts) and the poor maintenance thereof, the failures of the structures and in the vicinity thereof are also liable to increase in number.

Flood fighting activity in preceding centuries and systematic research conducted since 1995 have produced a collection of more than 2200 historical data regarding dike failures in the Carpathian-Basin. 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 dike 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 dike breaches.

The expected length of a dike 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 the Carpathian-Basin. Neither breach length results, nor the temporal trend of breaches contradict the laws of physics.

Although quite a few factors, such as the geotechnic properties of dikes, 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 compute technically sound estimates of expected breach length along certain rivers or river sections and the estimates can be used in localization calculations.

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