PERIODICA POLYTECHNICA SER. CIV. ENG. VOL. 50, NO. 2, PP. 125–139 (2006)

ESTIMATING DIKE BREACH LENGTH FROM HISTORICAL DATA

László NAGY

Department of Geotechnics
Budapest University of Technology and Economics
H–1521 Budapest, POB. 91. Hungary
e-mail: lacinagy@mail.bme.hu

Received: Sept. 14, 2005

Abstract

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. [14, 15] 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.

Keywords: Dike breach, historical data, estimate breach length, risk assessment.

1. Introduction

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 catchment.

In Hungary – situated in the deepest part of the Carpathian-basin - flood plains make up 22.8 per cent (21 248 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.

2. Levee Breach Length

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.

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[1] registers hundreds of dam failures [6, 7, 8, 21]. 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.

Fig. 1. Dike Breach in England November 2000.

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 levee breach. the project studies dike failures using on site large sample tests, small sample 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.

[1] International Commission on Large Dams

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,
- 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.

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.

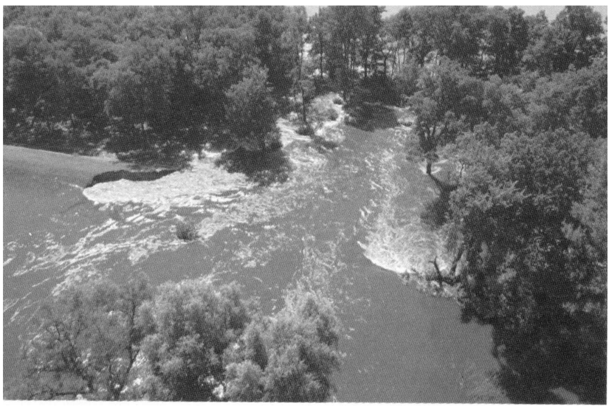

Fig. 2. Dike Breach at Oder river left bank at Frankfurt am Oder in 23 June 1997.

3. The Shape of Levee Breaches

Levee 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 levee breaches. (*Figs 1* and *2*)

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. (*Figs 4, 5, 6*)

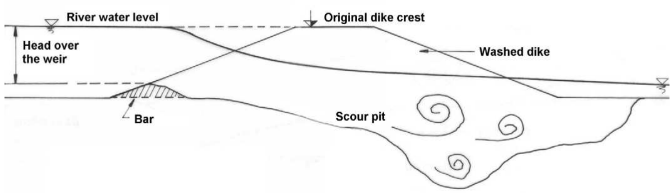

Fig. 3. Typical cross section of a dike failure.

A study of levee breach 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. (*Fig. 3*) This piece of earth is frequently called bar (*Figs. 8, 10* and *11*) 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.

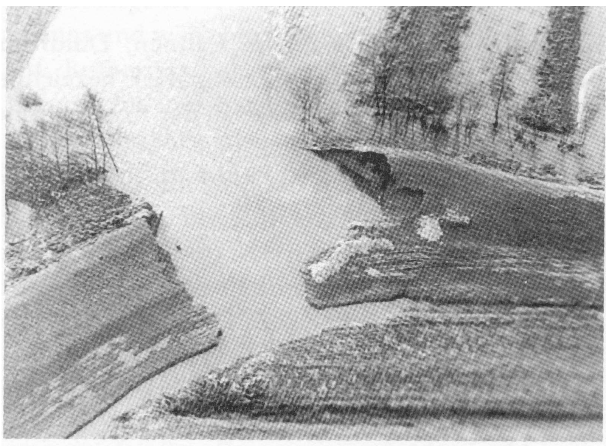

Fig. 4. Elba river left bank at Dorctersen in 3. January 1976 (Germany).

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

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

Fig. 5. Kettős-Körös flood in 1980 Hosszúfok dike breach (Hungary)

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 levee, 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. (*Fig. 13*) The dike failure on (*Fig. 14* also shows a scour pit that progressed to reach the water side on the left bank of the Tisza at Királyháza in the Ukraine in 1998.

4. The Overflow Height of Spilling Water

The longest levees breaches that occurred in the Carpathian Basin are presented in *Table 1*. Practically, each one of these dike failures

- occurred 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,
- occurred in the 19^{th} century, when levees were very much inferior in size,
- inundated spacious flood areas, i.e. large volumes of water could spill across the breaches.

Fig. 6. Breach at Tisza right bank in 2001 (Hungary).

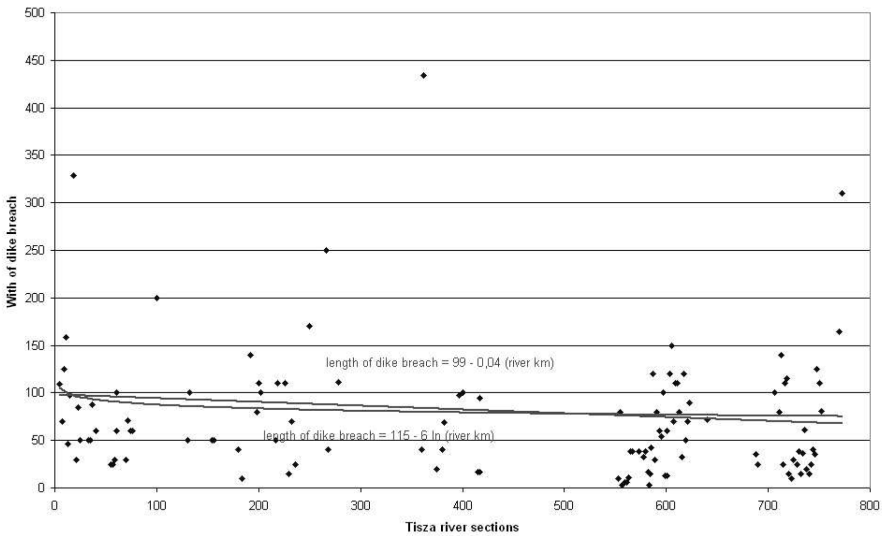

Fig. 7. Length of dike failures distributed by the profiling of the River Tisza

Of the 329 dike failures along the Tisza in the past 150 years, breach length is known in the cases 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 levees along 800 kilometers practically downstream from Huszt.

Table 1. The longest (>250 m) dike breaches in the Carpathian-basin

year	river, bank	piece	place	length (m)	source
1809	Duna left bank	3	between Szemeth and Gutor villages at the Gutor narrow	2100	[5],[12]
1809	Duna right bank	6	between Doborgaz and Vajka villages stopped the ice	1240	[5],[12]
1838	Duna left bank	1	at Géderlak, at the 1530 km river section, near the Paks village	300	[22]
1849	Duna left bank	2	between Vajka and Süly villages.	1400	[5]
1876	Duna left bank	2	between Kolozsnéma and Kiskeszi	1500	[19]
1876	Duna right bank	1	at Érsekcsanád village.	750	[22]
1876	Duna left bank	1	at Aranyos village, 85 houses collapsed	300	[12]
1876	Vág-Duna right bank	1	at Keszegfalu village, from 180 of houses 185 collapsed.	1000	[22]
1876	Duna right bank	1	at Szilágyi, between 6–7 km dike sections	758	[11],[22]
1876	Duna right bank	1	at Somfova, between the 16-17 km dike sections	337	[11],[22]
1876	Vág left bank	1	at Janki–Kapoly	400	[22]
1876	Tisza right bank	1	under Csany village.	380	[9]
1876	Duna right bank	1	at Kuskovác not far from Vajszka, collapsed 60 houses	300	[2]
1879	Tisza right bank	1	under Tiszakécske at Újkécske guard house.	1300	[12]
1880	Duna left bank	1	over Komárom	600	[21],[12]
1881	Szamos left bank	4	between Angyalos, Sályi and Porcsalma villages.	1162	[12]
1882	Tisza right bank	1	at Gradiska high bank	800	[12]
1888	Tisza right bank	1	under Tivadar village.	8000	[11]
1888	Tisza left bank	5	on the high bank between Tiszabő and Fegyvernek villages.	2170	[22]
1897	Duna right bank	1	not far from Vének village.	300	[4]
1899	Duna left bank	1	at Csicsó at the 1797 km river section.	255	[17]
1965	Duna left bank	1	at Kamariste village, breach caused a piping.	700	[3]
1970	Szamos right bank	1	23+040 km, at city Szatmár	650	[[18]

Fig. 7 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.

5. The Length of Levee Breaches along the River Tisza

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 *Fig. 3*, 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 a single meter only.

Consequently, doing nothing else but reducing the height of the 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.

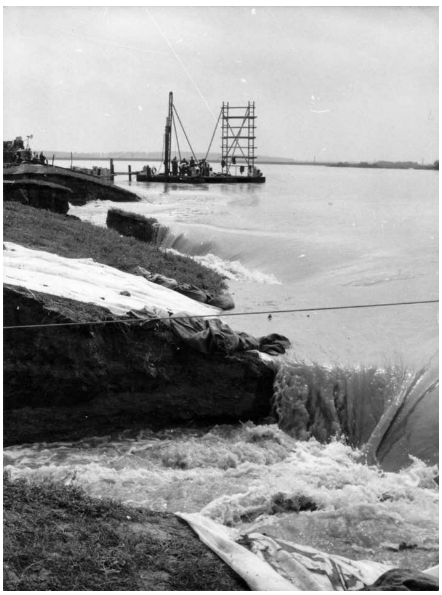

Fig. 8. Dike breach at Szeghalom in 1980 (Hungary)

Overflow height may be reduced by constructing a stilling basin on the protected side. 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. [16] Dike failure was imminent, but flood fighters intervened rapidly and laid sandbags to construct supporting ribs and deterred the direct threat. (*Fig. 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.

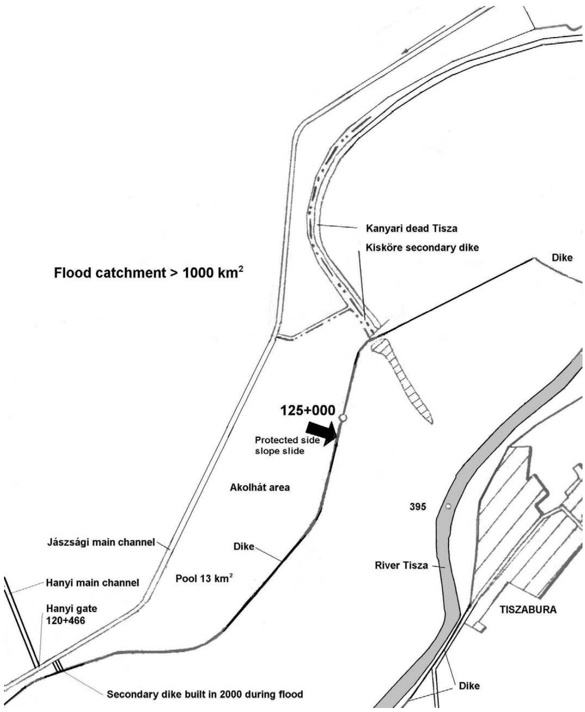

Fig. 9. General plan of Akolhát surroundings

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 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. 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 weights.

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 be 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 levee away right down to the level of the terrain, it washed away more or less of it.

Fig. 10. Dike breach at river Túr left bank in 2001 (Hungary)

It is only 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[2]. Only 99 of the 142 known long dike failures along the Tisza would allow such an approxi-

[2] Within the range of 10-15 km.

mation. In several cases we should use 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 be 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 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 laden 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 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 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[3] with actual fact 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).

Fig. 12 points out no more than the tendency of the relationship between the head over the weir and the breach length. 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 (*Fig. 12*). 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.

The two points in the left hand side of *Fig. 12* indicate high ground[4] overflows.

---

[3] 10% of the height of the levee.

[4] 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.

Fig. 11. Another dike breach at river Túr left bank in 2001 (Hungary)

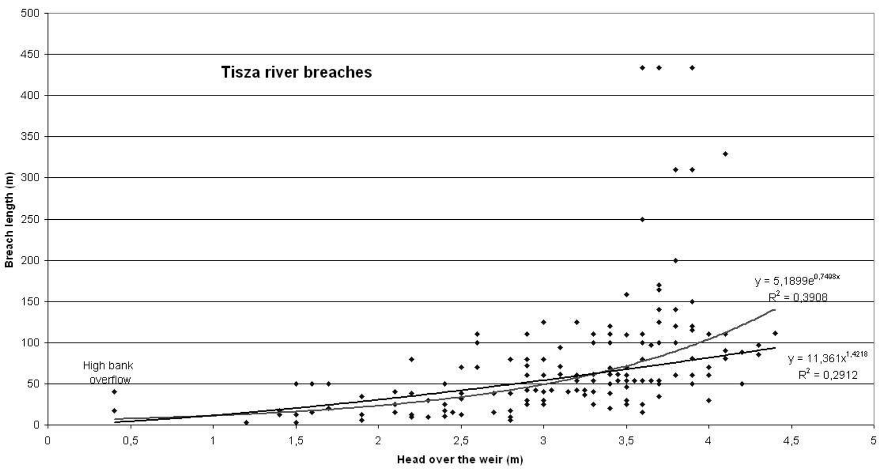

Fig. 12. Head over the weir and the length of a dike breach

6. Conclusion

The final length of the dike breaches we can estimate only on the base of historical data. The length of dike breaches along the Upper Tisza is not at significant variance with downstream data. 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 (*Fig. 12*). That is probably due to the multitude factors that are at play. The results do not contradict the physical law that raising the height of the overflow will increase the boundary shear of the water, which corresponds

Fig. 13. Hosszúfok dike failure during the Kettős-Körös flood in 1980

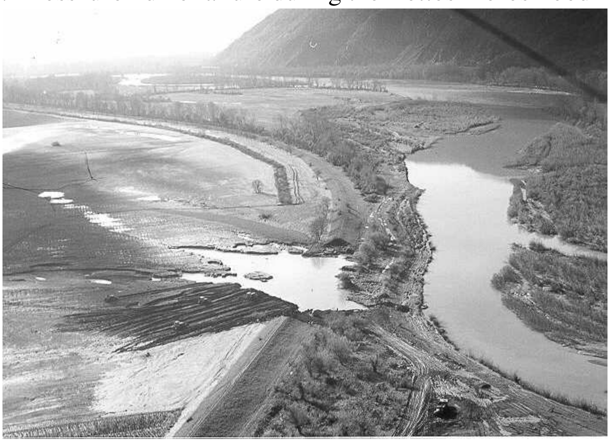

Fig. 14. Dike breach at Korolevo in1998 November (Ukraine)

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.

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 the Carpathian Basin. Neither breach length results, nor the temporal trend of breaches contradict the laws of physics.

References

[1] ASCE/USCOLD (1988), Lessons from Dam Incidents.

[2] BERECZ, K. (1896), A Gombos-Vajszkai Ármentesítő és Belvízszabályozó Társulat Monographiája, Légrády testvérek, (Monography of the Gombos-Vajszka Flood Control Association), Budapest, in Hungarian.

[3] BODY, K. – CSOMA, J. – KÁROLYI, Z. – SZILÁGYI, J. Az 1965 évi Dunai árvíz hidrológiai okai és lefolyása, The Hydrology of 1965 Year Danube Flood, *Vízügyi Közlemények*, (1966), pp. 51–102, in Hungarian.

[4] FEKETE, M., Rábaszabályozó társulat történeti áttekintése (Historical Overview of River Rába Regulation Association 1873–1948), manuscript, (1950), in Hungarian.

[5] FÖLDES, GY. Felső-Csallóköz árvízvédekezésének története , (History of the Upper-Csallóköz Flood Control)(1896), in Hungarian.

[6] ICOLD (1981), Lessons from Dam Incidents.

[7] ICOLD (1984), Word Register of Dams.

[8] ICOLD (1995), Dam Failures Statistical Analysis.

[9] KARDOS, I. Szeged árvízvédelmi rendszere (Flood Control System of City Szeged), ATIVIZIG, Szeged, (1975), in Hungarian.

[10] KORBÉLY, J. A Tisza szabályozása (Tisza River Regulation), Magyar Nemzet Könyv és Lapkiadó, Debrecen, (1937), in Hungarian.

[11] KOVÁCS, D. edited, Árvízvédelem, folyó és tószabályozás, vízi utak Magyarországon, (Flood Control, River Regulation and Lake Control, Water Ways in Hungary), National Water Authority, (1979), Budapest, in Hungarian.

[12] KVASSAY, J., A Duna- és Tiszavölgyi ármentesítő társulatokra vonatkozó statisztikai adatok (Statistical Datas of Danube and Tisza Valley Flood Control Associations), Pátria Irodalmi Vállalat és Nyomdai Rt., Budapest, (1900), in Hungarian.

[13] KVASSAY, J. A vízi társulatokra vonatkozó statisztikai adatok (Statistical Data Regarding Water Associations), Pallas Rt., Budapest, (1913), in Hungarian.

[14] NAGY, L., Árvízvédelmi gátak szakadásai (Breaches of Flood Dikes), R+D report, (2001), in Hungarian.

[15] NAGY, L. Árvízvédelmi gátak szakadásai, a szakadások statisztikai vizsgálata (Breaches of Flood Dikes, Statistical investigation of breaches), R+D report, (2002), in Hungarian.

[16] NAGY, L. (2004), Length of Historical Dike Breaches at Tisza River, under press, Vízügyi Közlemények, in Hungarian.

[17] PÉCH, J., Gátvédelem, Gyakorlati kézikönyv vízi mérnökök és gátvédők részére (Dike Protection, Practical Guidebook for Civil Engineers and Flood Defence Engineers), Budapest, (1892), in Hungarian.

[18] SZEIFERT, GY., Árvízvédelem a Tisza-Szamos-Kraszna közben, Flood Control in the Area between Tisza-Szamos-Kraszna Rivers, *Vízügyi Közlemények*, (1971), pp. 75–94, in Hungarian.

[19] TŐRY, K., A Duna szabályozása (The Regulation of River Danube), Budapest, Akadémiai Kiadó, (1952), in Hungarian.

[20] TRUMMER, Á., Az idei országos árvíz (1940), (The 1940 year flood), *Vízügyi Közlemények*, In Hungarian.

[21] US ARMY CORPS of ENGINEERS (1992), Stability Evaluation of Existing Levees for Benefit Determination, *Technical Letter* No. 1110-2-328.

[22] ZAWADOWSKI, A.Magyarország vizeinek statistikája I-II (1891), Statistical Data of Hungarian Waters. I.-II., M. Kir. Statisztikai Hivatal, Budapest, In Hungarian.