Causes of dike deterioration – environmental and anthropogenic effects

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Summary

The flood protection embankments of Hungary and Europe face challenges. Previously unprecedented droughts and low-water periods in the rivers are experienced. As a consequence, the water balance of the dikes can alter and desiccate in the long term. The most staggering fissures appeared on dikes built from clays susceptible to volume change. The safety aspects of these fissures are not fully understood. The concerns raised depend on the crack's spatial extent, the material of the dike and the environmental effects, such as heavy rains and floods. The General Directorate of Water Management ordered a comprehensive survey of dike pavement cracks in Hungary. It was a nationwide survey. Hungary has about 4,400 km of primary flood protection embankments, out of which 1,250 km are paved. There are a number of reasons why the pavement of an embankment can crack. The main intention of this paper is to classify the primary and secondary sources of pavement cracks on flood protection embankments. The main features of crack patterns related to clays with shrink-swell potential are identified.

Keywords: pavement crack survey, dikes, swelling-shrinking clays, safety aspects, climate change

Árvízvédelmi töltések károsodása – környezeti és antropogén hatások

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Összefoglalás

Magyarország és Európa árvízvédelmi töltései számos kihívással néznek szembe. Az egyik legjelentősebb az éghajlatváltozás következtében jelentkező szélsőséges időjárás. Az elmúlt évtizedek során az árvizeket gyakran hosszan tartó aszályok követték, a folyóink vízállása az aszályos nyarak során rekord alacsony értékeket mutat. A vízhiány következtében a gátak óhatatlanul kiszáradnak, burkolt vagy burkolatlan koronájuk megrepedezik.

Mintegy 4400 km elsődleges árvízvédelmi töltés található hazánkban, ebből 1250 km burkolt. Számos hatás idézhet elő töltésburkolat-repedéseket. Jelen cikk fő célja az árvízvédelmi töltések burkolatrepedései elsődleges és másodlagos forrásainak osztályozása, a köztük lévő kapcsolatok feltérképezése. A zsugorodási-duzzadási potenciállal rendelkező agyagokhoz kapcsolódó száradási repedésminták főbb jellemzőinek meghatározása. A felmérés fontos hozadéka, hogy a repedés geometriája és a töltés anyaga következtetni enged a repedés kialakulását előidéző folyamatokra.

2018-ban országos felmérés készült a burkolatrepedésekről az Országos Vízügyi Főigazgatóság megbízásából. Az árvízvédelmi töltésburkolat-repedés felmérése, a töltés és a burkolatrepedés geometriai tulajdonságai mellett az adott szakaszok rétegrendjét, töltésanyagát és a kialakuláshoz vezető folyamatokat is dokumentálták a felmérők. Az eredményeket, a levonható konklúziókat és a felmérés korlátait is tárgyaljuk.

A repedéseket hat jól elkülöníthető kategóriába sorolhatjuk irányultságuk alapján, ezeket a tanulmány részletezi. A kialakulásuk három legfőbb oka a töltéskonszolidáció, az aszály következtében létrejövő száradási (zsugorodási) repedések, és az árvízhez köthető károsodások. A Tisza és mellékfolyóinak repedezett töltései szinte kizárólag kötött talajból épültek, míg a Dunántúlon sokszor átmeneti vagy szemcsés talajt is használtak a töltés építéséhez.

A hosszirányú komponenssel, illetve a repedés két széle közötti magasságbeli különbséggel rendelkező károsodásokat zsugorodás okozhatta. A térfogatváltozó talajok és a hozzájuk köthető zsugorodási burkolatrepedések a Tisza és mellékfolyóira jellemzők.

A feltárt repedések biztonsági vonatkozásai nem teljesen ismertek. Ez függ a repedések térbeli kiterjedésétől, a töltés anyagától és a környezeti hatásoktól, mint például a heves esőzések, árvizek. Az Országos Vízügyi Főigazgatóság által rendelt felméréshez hasonló átfogó adatgyűjtést Európában még nem végeztek, Amerikában is csak az egyes államok megyéire terjedtek ki útburkolat-repedés felmérések. A jelentősebb repedések évenkénti felmérése célszerű lenne, hiszen információhoz jutnánk a terjedésükről. Hány évvel a töltés vagy a burkolat átadása után jelennek meg? Egy aszályos nyár után nő-e a repedések kiterjedése?

Kulcsszavak: töltések burkolatrepedés felmérése, árvízvédelmi töltések, duzzadó-zsugorodó agyagok, biztonsági aspektusok, éghajlat változás

Forewords

The present study is based on the 2018 embankment pavement survey coordinated by the General Directorate of Water Management and carried out by the Regional Water Directorates; the survey was evaluated by the author, Zsombor Illés, and his PhD supervisor, László Nagy. Such comprehensive flood protection embankment pavement crack surveys have not been conducted in Hungary before. In international practice, only small-scale surveys have been carried out. The cracks observed in paved embankments are a good indicator of the volume change processes occurring in the embankment because:

1. In the case of embankments with unpaved crests, surface cracks can close, and information can be lost.
2. Dikes are expected to have low vehicle loads outside the flood protection period, regardless of the number of units and axle loads. Therefore, the pavement layers are thinner, so the movement or the displacement of the dike can be better followed.
3. No base layer is applied underneath the pavement because its good water conductivity can lead to levee failure (overtopping).
4. The material of the flood protection embankments is predominantly clay, whose volumetric behaviour is well followed by the relatively thin linings.

The effects on the embankment can be assumed from the shape of the cracks. Deeper, more extensive cracks reduce the stability of the dike, but their exact mechanism of action is unknown. The survey and the research carried out by the PhD student are part of a series of flood protection embankment surveys in our country started in 1980. This research is aimed at understanding drying cracks in volume-variable cohesive soils. The causes responsible for their formation are explored in this publication.

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Regarding maintenance, development and flood protection operational activities, the proper maintenance and operation of primary flood protection and reservoir embankments are crucial for the water management sector. It is essential to ensure that they can perform their function in a proper condition during floods. Dike construction has been accelerated since the 19th century, followed by continuous upgrades and elevations, resulting in an "onion" structure. Significant EU-co-financed investments in embankment development and reconstruction took place in the last decade. In general, the operator of the flood protection embankment is confronted with various challenges, mainly of a geotechnical nature, due to the rudimentary construction technologies applied in the 19th century, when the core of the dikes was constructed. One of the most important manifestations of this is the drying of the embankments due to prolonged and heavy droughts. The shrinkage of clay resulting in the appearance of cracks or, even more importantly, fissures that are already larger than the self-healing of the clay can compensate.

Therefore, the study of phenomena related to desiccation crack formation in the embankment is highly relevant.

These phenomena are the main interests of the research carried out by the author in the Cooperate Doctorate Programme (KDP). The author has shown considerable autonomy in the preliminary design and the implementation of a dike monitoring system. After the successful installation, the system measures the soil moisture content and negative pore water pressure. The monitoring system – unique in Hungary – allows the investigation of desiccation processes.

Based on the research objectives of the KDP, it could help to address and prevent desiccation problems of the Hungarian dike system and enrich our knowledge where solutions are not yet scientifically validated.

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1. Introduction

Hungary is situated in Central Europe, drained by the Danube, in the deepest part of the hydrographic unit known as the Carpathian Basin. To the west, it is surrounded by the Alps, while to the north, east and southeast it is bounded by the Carpathian Mountains. The country's territory covers 93,000 km^2 and represents 11.4 % of the 817,000 km^2 large Danube catchment area. During the 19th century, the river regulation transformed the slow-flowing meandering Tisza river into a waterway that could be used for transportation and a huge portion of the flood plains were retrieved for agricultural use. The Carpathian Basin has approximately

11,000 km of flood protection embankments, almost half of it, 4,900 km (primary and secondary lines) is located in Hungary *(Nagy 2018)*. The dike system construction began more than 150 years ago. Since it has been continuously raised and strengthened *(Nagy 2006)*, this has resulted in a heterogeneous, so-called onion structure documented by a few authors *(Tóth–Nagy 2006; Schweitzer 2009; van Woerkom et al. 2022; Illés–Nagy 2022)*. The embankments are mainly constructed from materials locally available *(van Woerkom et al. 2022)*, using historic construction methods *(Dyer–Utili–Zielinski 2009)*, such as cross transportation. The flood protection embankments bear many construction errors like unsuitable earthwork materials, inadequate compaction, and unfavourable subsoil conditions.

There is growing empirical evidence that the length of the return periods of extreme hydrological events, such as floods and droughts, is decreasing, i.e. the frequency, or the probability of extreme events, is increasing, yielding more frequent disasters at both ends of the hydrological spectrum *(Szöllősi-Nagy 2022)*. These events indicate that the hydrological cycle has changed fundamentally. In recent decades floods have been rare in the Carpathian Basin. However, droughts are getting more frequent in Hungary, and the climate is becoming arider *(Bihari et al. 2018; Gavrilov et al. 2020)*, causing embankments to desiccate to an unseen extent. The Carpathian Basin is more exposed to the effects of climate change than most European regions *(Hungary Today 2021)*. In the past 120 years, according to the Hungarian Meteorological Service (OMSZ), warming was 1.1°C globally, while it reached 1.2°C in Hungary. The droughts of 2022 in Hungary were unprecedented; a significant amount of water has evaporated from Lake Velence, exposing the lake bed in shallower parts. The moderate continental climate of Hungary is shifting towards mediterranean. Periods of high temperatures and sunny days without precipitation will become more and more common. Summers are becoming longer, warmer and arider, while winters have become milder with more precipitation *(Kocsis 2018)*. The annual mean temperature *(Izsák–Szentimrey 2020)*, as well as the number of heat wave days (when the daily mean temperature is above 25°C) *(Kocsis 2018)*, show an uptrend. According to climate models, the extent of extreme droughts in the Carpathian Basin will increase due to climate change and geographic exposure. It has the most significant effect on the water content and pore water pressure of near-surface soil layers, as infiltration from precipitation decreases and evaporation increases due to the higher temperature *(Pap 2020)*. Climate change is having a serious impact on water resources. It is particularly true for the Danube river basin countries *(Balatonyi et al. 2022)*. Hungary, in terms of water security, is exposed to other countries. It is due to the downstream characteristic of the basin. The country is mainly plain and relies on the upstream countries of the Danube, Tisza, Dráva and Körös rivers. The spatial and temporal distribution of rainfall is uneven *(Kocsis 2018)*. This makes the downstream countries more dependent on the upstream countries for continuous inflow.

This article describes a survey that was conducted on the paved dikes of Hungary. The length of the paved primary flood protection system is 1,250 km long according to the local water directorate *(Illés–Nagy–Antal 2022)*. The pavement cracks are an indication of the degradation of the pavement and the deterioration of the earthwork itself. The presented survey can be used as a baseline for further dike pavement crack inspections. The primary (mainly environmental) and secondary (anthropogenic) causes of the pavement crack formations were identified, and their correlation is presented.

After the introduction, the article presents the survey's methodology, the results are summarised, and conclusions are drawn. The article discusses the security aspects of dike desiccation and the failure modes that it can trigger.

2. Methodology

The backbone of the research is the dike pavement crack survey ordered by the Országos Vízügyi Főigazgatóság (General Directorate of Water Management – OVF) in 2018. The survey was conducted by 12 territorial water directorates and supervised by the General Water Directorate. László Nagy (Ph.D., associate professor at BME) and Zsombor Illés (PhD student at BME) evaluated the survey. To the best of our knowledge, comparable surveys, somewhat smaller in scale, were made in the region of Al Ghatt in Saudi Arabia, *(Dafalla–Shamrani 2011)* and in Austin, Texas *(Jouben 2014)*.

Pavement cracks do not heal, this was the primary reason for analysing them. They are imprints of the effects on the dike crest. Dikes are paved for multiple reasons. The most important is to facilitate flood control operations. Inspections are more rapid and more straightforward. During flood protection operations, materials can be moved quicker and safer on the paved dike crests. The pavement material on the examined sections is as follows: 94.8% asphalt, 2.4% concrete cover and 2.8% sett *(Illés–Nagy 2022)*.

Asphalt pavement can sustain significant deformation due to the viscous nature of the bitumen binder, before eventually cracks become visible. This is an advantage from a maintenance point of view but a drawback from a monitoring aspect, as cracks appear with a delay on the crest.

Altogether 1,250 km of paved flood protection embankment was inspected, and 1,987 smaller or bigger fissures were detected, which means an average of 1.6 cracks km^{-1} *(Illés–Nagy 2022)*.

The following characteristics of the fissures were collected during the survey:

- Location of the crack(s) on the embankment (most of them appeared on the crest of the embankments, 97% of all cracks),
- Orientation of the crack(s) compared to the axis of the embankment,
- The extent of the crack(s) on the surface of the pavement,
- The thickness of the crack(s),
- Height difference (dislocation) between the two sides of the crack,
- Number and location of fissures (few, more parallel cracks, network of cracks),
- The aspect of cracks (crease, patched, wheel track – rutting, side rapture, sinkholes, etc.),
- The reason behind the crack formation,
- Environmental causes of the crack formation (floods and droughts).

The geometry, location and aspect of cracks were documented by photo(s). The same characteristics were documented by other surveys: *Dafalla–Shamrani (2011); Jouben (2014); Chotkan (2021)* – in the latter case grass covered dike crests were inspected.

To be able to form a database of the examined sites and embankments, the following parameters were used in the study:

- Identification number of territorial water directorates (1 to 12),
- Sign of flood protection embankment,
- River and side (left, right),
- Sectioning (embankment section marker),
- GPS coordinates of the crack,
- Elevation of the dike,
- The embankment's axis compared to the north, in degrees,
- The subgrade of the embankment under the pavement.

2.1. Crack location

The width of road pavement is roughly 3 m. According to the schematic picture *(Figure 1)* it is divided into three strips, each of them of 1 m width. After evaluating the pictures and the received answers, the crack appearance was classified into the following groups: i) fractured sides, ii) cracked axis, and iii) fissures throughout the cross-section. There was no differentiation between cracks appearing on one or both sides. The flood plain on the waterside of the flood protection embankment is usually covered with some vegetation (floodplain forest), while the protected side is agricultural land. Some dikes can hold water from both sides as they surround flood retention reservoirs. The flood side is not relevant in emergency reservoirs, and if the sides are not known, it might not be easy to decide just by a photo.

Figure 1 Position of fissures on the paved dam crest

Source: Nagy, 2019

2.2. Crack orientation

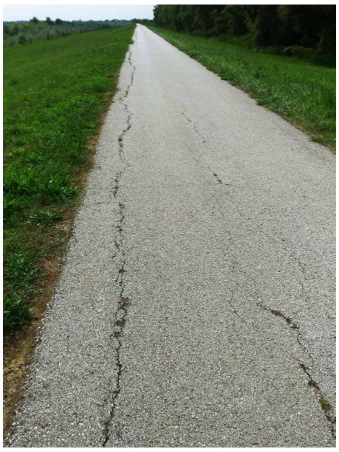
The orientation of the cracks was compared to the road axis. They were classified into six categories. The categories are the following: i) cracks parallel to the road axis, ii) perpendicular to the axis, iii) combination of parallel and perpendicular cracks (block cracking belongs to this category), iv) diagonal or winding cracks, v) undetermined (there are extreme cases of ravelling and flushing, causing total pavement failure, in these cases, the crack directions are not visible). The categories are presented in *Figure 2.* In a few cases, sinkholes were also documented. A category referred to as 'no data' was created for cases where the crack direction was not mentioned or not visible. This categorisation was first presented in *Illés–Nagy–Antal (2022)* and in *Illés–Nagy (2022).*

2.3. Crack extent

In the case of a single crack, its length was measured. If it was a group of interconnecting fissures, such as a crack group, then the surveyor estimated the area. Both of these were converted to cracked dike length.

2.4. Crack thickness

To classify the crack thickness the following categories were defined based on the survey results: i) thin, ii) medium and iii) thick. The first two categories (thin and medium) indicate an issue with the pavement or with the sublayers (pavement work gap, heavy traffic). The thin category can also be regarded as hairline cracks. Only the 1–2 mm diameter cracks are classified into this group. The medium-thick cracks have an approximate breadth of 2–5 mm, while sturdy (thick) cracks are thicker than 5 mm. These relatively wide cracks, often coupled with

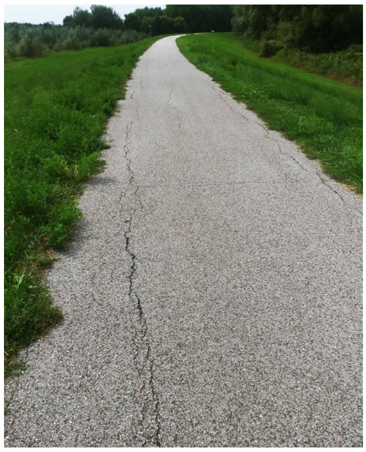


i) Parallel

Tisza, Left bank 3+600

ii) Perpendicular

Moson-Danube, Left bank 16+173



iii) Parallel + Perpendicular (a)

Tisza, Left bank 2+500

iii) Parallel + Perpendicular block cracks (b)

Tisza, Left bank 55+300

iv) Winding

Tisza, Left bank 56+250

v) Undetermined

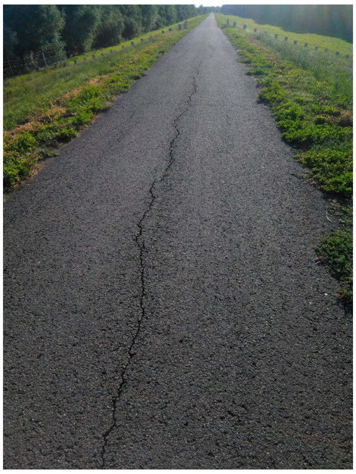
Tisza, Right bank 41+210

Figure 2 Crack direction compared to the axis of the embankment

Source: Nagy, 2019

i) Thin (hairline)

Tisza, left bank, 0+690



ii) Medium

Tisza, right bank, 7+230

iii) Thick (sturdy)

Tisza, right bank, 126+260

Figure 3 Crack width; thin (1–2 mm), medium (2–5 mm) and thick (>5 mm)

Source: Nagy, 2019

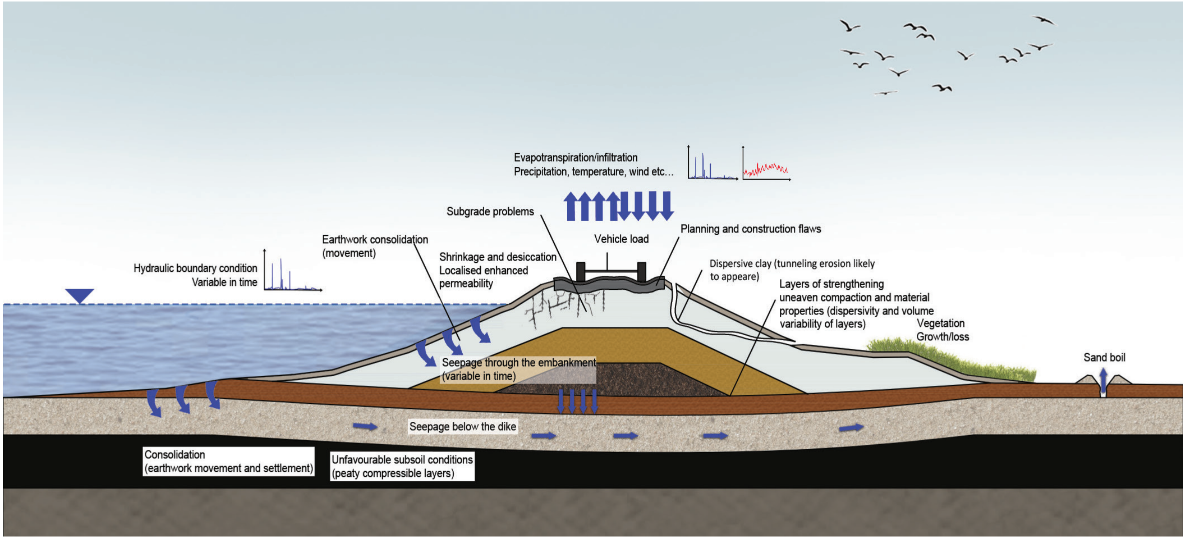


Figure 4 |

pavement deflection *(Jouben 2014)*, mark soils with volume variable properties in the embankments. The thickness of the crack was measured by the surveyors, measured or approximated from the photos. The crack width categories are demonstrated in *Figure 3.*

2.5. Environmental and human causes of crack formation

In the survey, it was explicitly asked whether the crack appeared due to flood or drought. A considerable number of answers indicated that both environmental phenomena contributed to crack formation.

A general inquiry was made about the cause of the dike pavement fissuring. The results of the answers will be summarised later. Thus, for the crack formation, we distinguished primary and secondary causes. The assumption was made that pavement cracks on low-traffic roads such as dikes are generally caused by environmental effects. These effects were considered as the primary cause. However, design and construction errors, lack of maintenance, and occasional heavy traffic can also contribute to deterioration. These were the secondary causes. These effects are illustrated in *Figure 4.* When no environmental effect was mentioned, the secondary and primary causes were the same. The decision-making mechanism is presented in *Figure 5.*

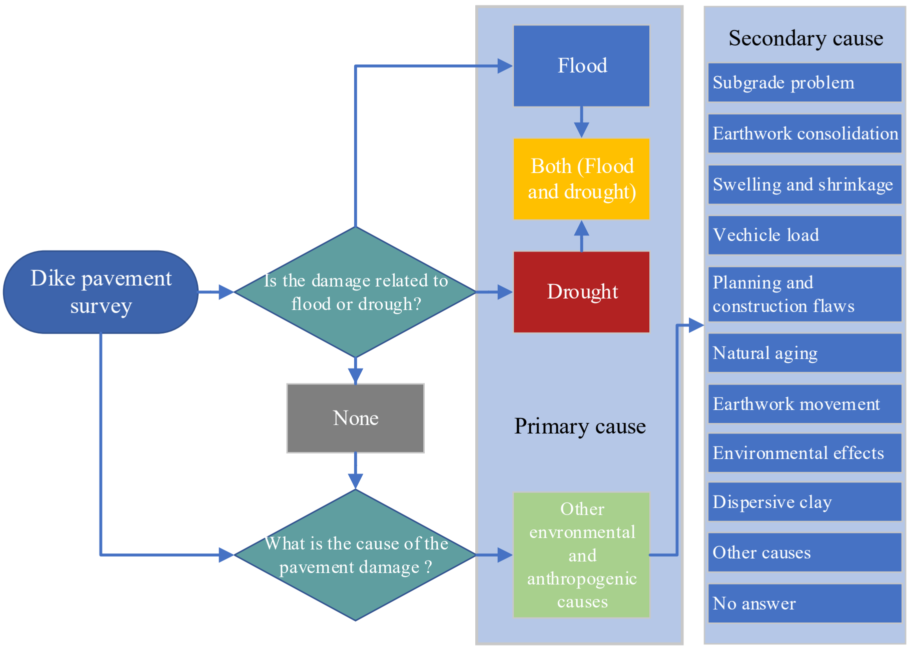


Figure 5 | Distinguishing primary and secondary causes of pavement deterioration

Own source

Table 1 Number and length of pavement cracks in the catchment area of the Danube and Tisza

Catchment area	[-]	Danube	Tisza
No. of cracks	pc.	1,158	829
Length of cracked pavement	m	31,960	24,7704
Length of paved dikes	km	360	890
Specific number of cracks	pc/km	3.22	0.93
Specific cracks	m/km	88.78	278.32
Average dam height	m	3.20	3.78

Source: Illés–Nagy, 2022

2.6. Dike material of the sections with cracked pavement

The results regarding the dike material are entirely based on the survey sent to the Water Directorates of Hungary. A database of recent soil mechanical investigations in the cracked sections was presented in *Illés–Nagy (2022)*.

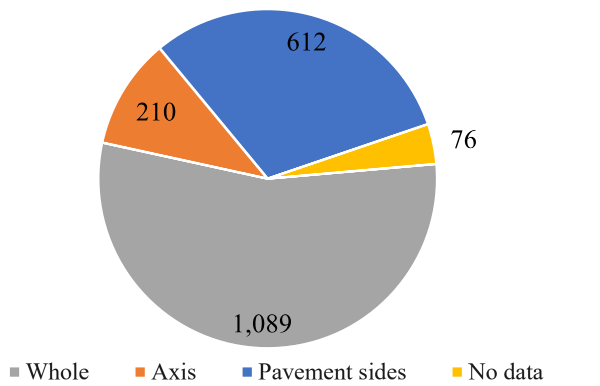


Figure 6 Summation of the location of cracks at the paved cross-section

Source: Nagy, 2019

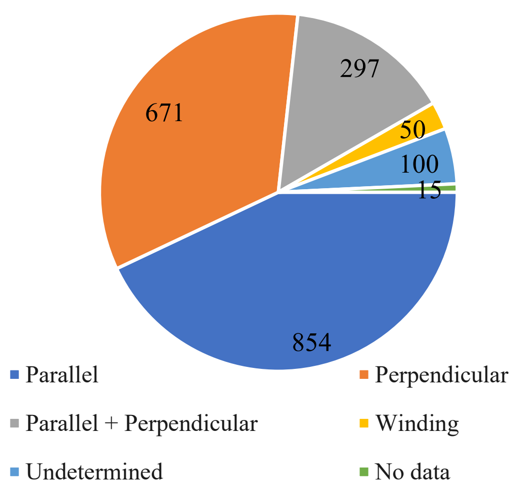


Figure 7 Proportion of crack direction compared to the axis of the pavement

Source: Nagy, 2019

3. Results of the survey

In this part, the results of the pavement crack survey are presented. The results in correlation with flood and drought maps are also given.

According to the methodology described in the previous section, *Table 1* presents the number of cracks and the length of the cracked embankments. The values are summarised separately for the Danube and the Tisza catchment areas. The water management of the two rivers differs. The behaviour of floods, embankment materials and their height also vary in these regions. Besides the number and length of cracked pavement, the length of paved flood protection embankments managed in the territories, and the specific number and length of cracks are also shown in *Table 1*.

In the Tisza catchment area, the dike system is usually higher and longer than in the Danube region. The num-

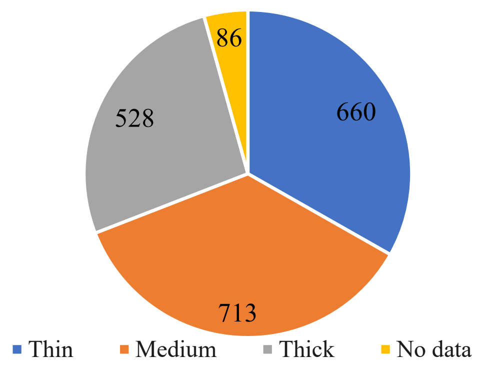


Figure 8 Summation of each crack width category

Source: Nagy, 2019

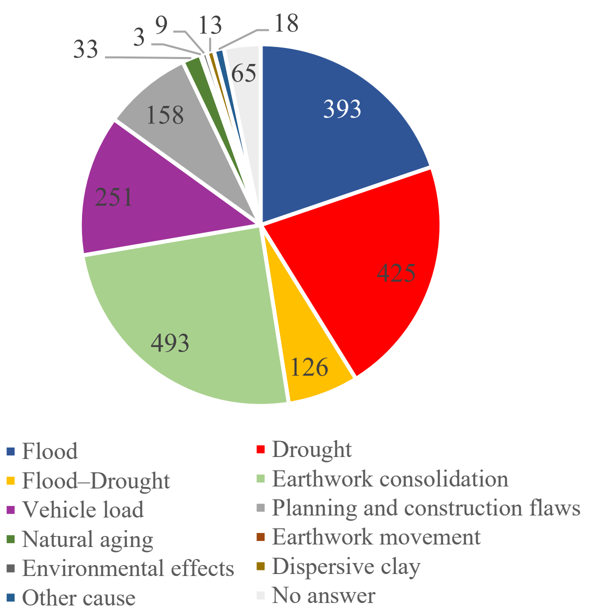


Figure 9 Primary causes of the flood protection embankment fissures

Own source

ber of pavement cracks are fewer, but they tend to be longer in the Eastern part of Hungary (i.e. where the Tisza and its catchment area are located).

Furthermore, results regarding the spatial distribution of cracks on the pavement, their direction and thickness are evaluated. Finally, the dike materials under the cracked cross-section are overviewed.

3.1. The spatial extent of the cracks

This subsection evaluates the crack location, direction, and thickness results. The answers to the survey were classified according to the methodology section.

If the pavement at the central strip and at least one of the side strips were fissured, the whole cross-section was considered fissured. This consideration may indicate that the entire cross-section is fissured in more than half of the cases, as presented in *Figure 6*.

The ratio of the six crack direction categories (see *Figure 2*) are presented in *Figure 7*. More than a third of the cracks are parallel with the road axis.

The ratio of the demonstrated crack width categories is given in *Figure 8*.

Apart from the crack's spatial features, another important aspect is the assumed origin of the fissure. The appearance and the cause of the crack are correlated.

3.2. Causes of crack formation

Part of the survey dealing with the causes of crack formation is summarised in this subsection. Identification of the primary and secondary causes of crack formation were carried out according to the decision-making tree presented in *Figure 1*.

3.2.1. Primary causes of crack formation

The primary causes of the fissures identified by the pavement survey of the flood protection embankments are given in *Figure 9*.

It is challenging to visualise the connection between the primary and secondary causes responsible for the pavement fissure development of the dikes. Only those cases were featured where the primary and the secondary cases differed (944 out of 1,987). The connections are presented in a graph (see *Figure 10*). The rectangles represent the primary causes (Flood, Drought, Flood–Drought), while the horizontal oviforms are the secondary causes. *Figures 9* and *10* clearly show that the effect of droughts is as concerning as floods.

The fissure's location and the primary cause are marked on Hungary's drought and flood probability maps (see *Figure 11*). The driest region of Hungary is the Hungarian Great Plain, which falls into medium-drought, heavy- and extremely heavy-drought zones – approximately 40% of Hungary's territory and 75% of the agricultural areas in the country. It is more or less 28,000 km^2 *(Pálfai 2004)*. On the other hand, flood probability zones occupy the Great and the Small Plain, where the rivers have vast areas to flood in case of a dike breach.

3.2.2. The secondary causes of crack formation

The usage of volume-variable soils should be avoided. Soils with swelling and shrinkage have a high smectite content. The principal clay mineral responsible for the expensive behaviour is montmorillonite. High montmorillonite content has been detected in dikes in Hungary *(Illés–Nagy 2022)*. Due to climate change, droughts are becoming more frequent, and desiccation cracks are documented on the crest of the dike. Drought as a pri-

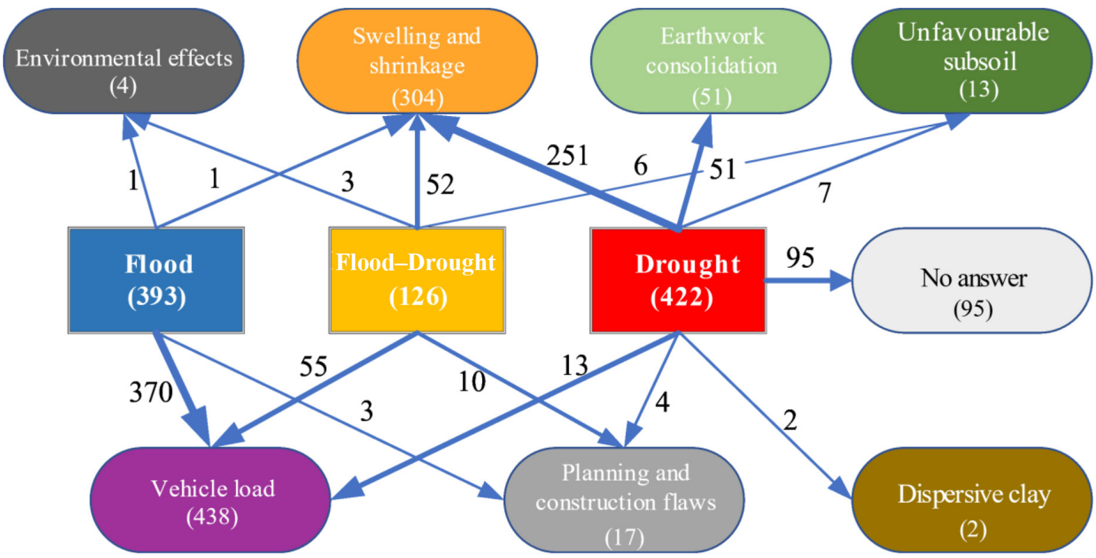


Figure 10 Relation between the primary and the secondary causes

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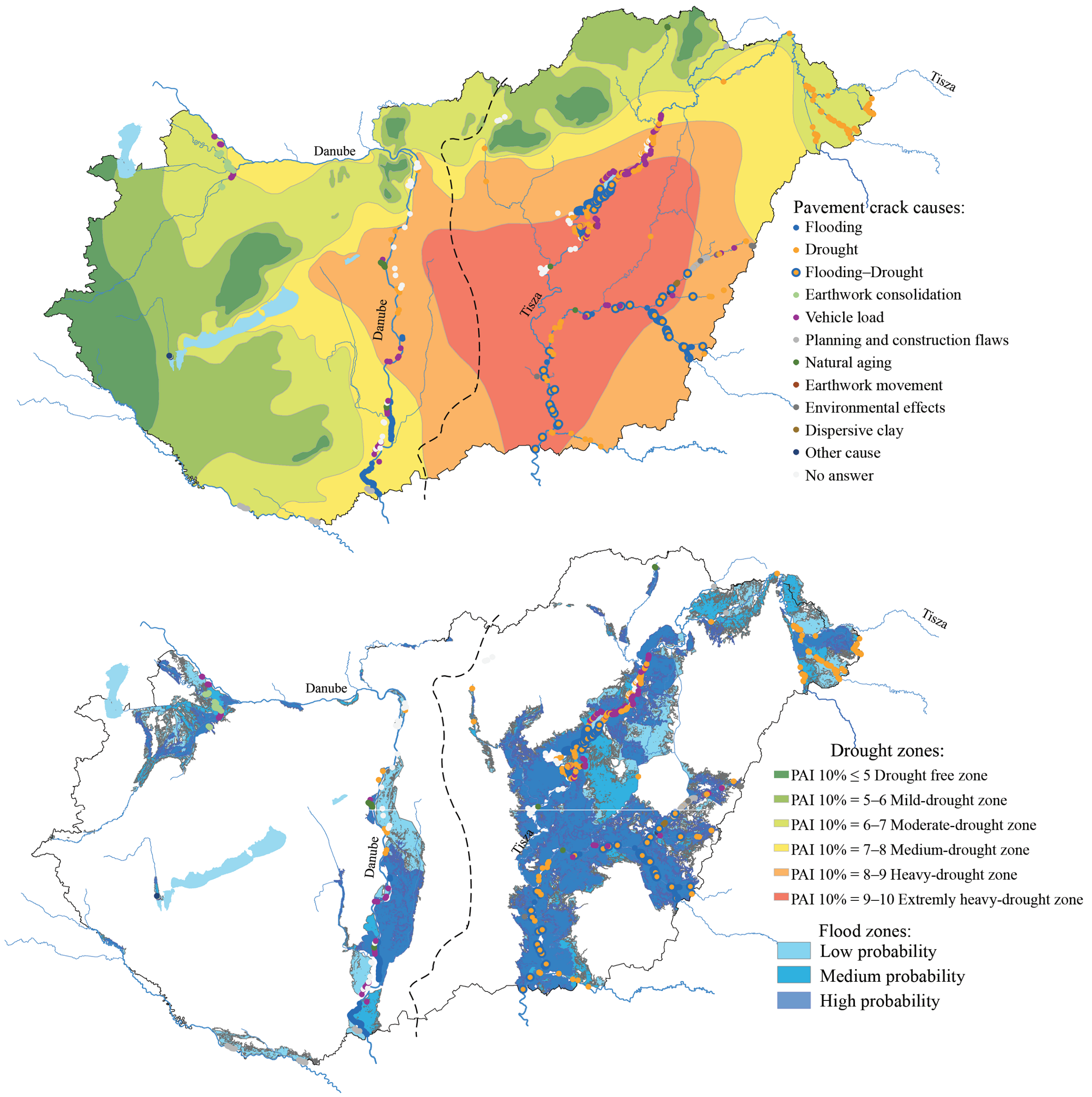

Figure 11 Aridity and flood probability maps of Hungary (provided by OVF) with the coordinates of the pavement cracks
Own source

mary cause and swelling and shrinkage as a secondary cause are closely linked *(Figure 10)*.

Soil consolidation is the settlement caused by the compression stress of a load, such as the soil layers of an embankment. The volume of a partially or fully saturated soil decresases due to the stress acting on it *(Terzaghi-Peck 1967)*. The vertical displacements are elongated in time, and their values can be calculated from laboratory experiments (Oedometer test) *(Taylor 1948, Kézdi 1976)* or test embankments.

Unfavourable subsoil conditions include compressible peaty and organic layers and old river bed crossing *(Nagy 2000)*. Due to the river regulation works, the meanders of the Körös rivers were dissected, creating crossings and built-in hazards of the old river bed *(Tímár 2020)*.

A group of soils, dispersive clays, were constantly mentioned in *Figures 5, 9*, and *10*. It is easy to spot the erosion signs on the embankments constructed from these clays. They are susceptible to tunnelling erosion (International Commission on Large Dams *(ICOLD 1990)*). Their existence was first documented in North America, Australia, and the Indian subcontinent *(Granth et al. 1977)*. During the 20th century, pinhole and double hydrometer tests were used to identify them *(Sherard–Dunnigan–Decker 1976; Rosewell 1977)*. Their presence is also frequent in Hungary, between the river Danube

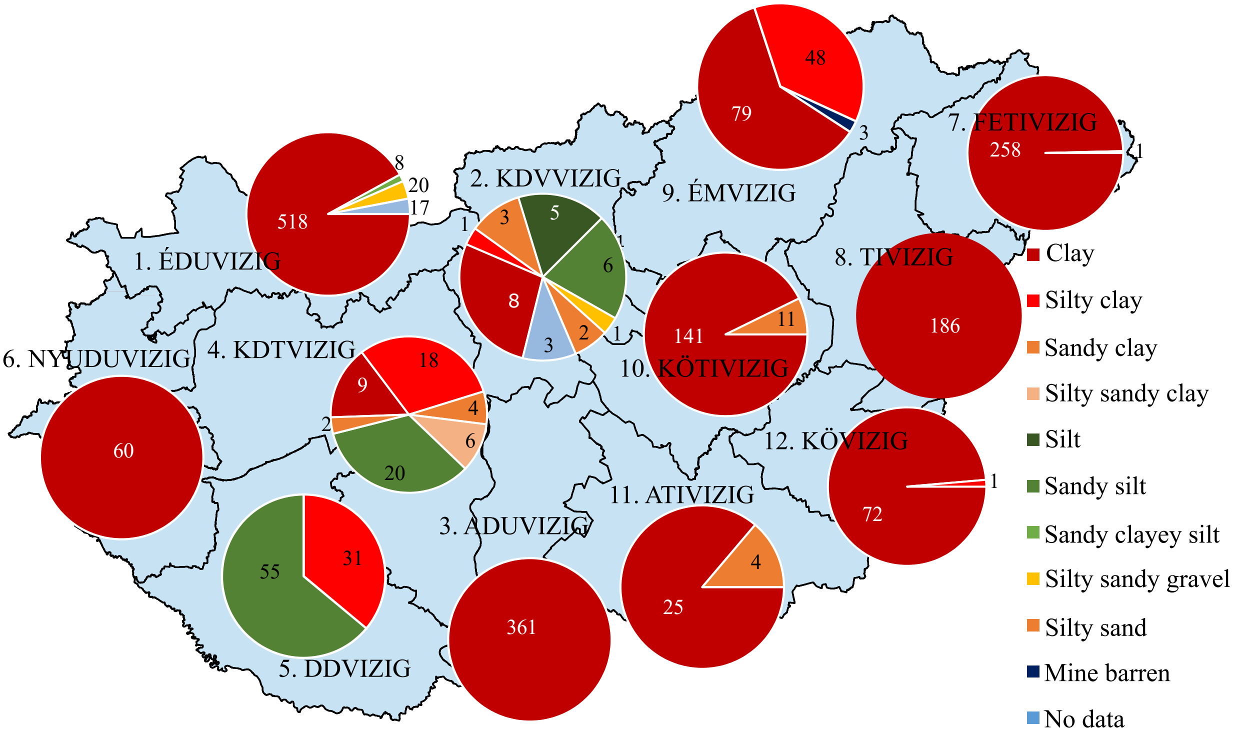

Figure 12 Dike material under the cracked pavement section at each water directorate

Source: Illés–Nagy–Antal 2022

and Tisza saline lake beds containing these types of cohesive soils *(Nagy et al. 2021)*, and they are present along the Tisza and their tributary rivers *(Szepessy 1981; Nagy–Nagy–Illés 2015)*. The dispersive nature of the soils (and their pinhole test results) were linked to their physico-chemical properties *(Nagy–Nagy–Kopecskó 2016; Nagy–Nagy 2016)*.

Planning and errors mainly include pavement and cover design shortcomings such as i) too thin pavement layers, ii) lack of protective layer, and iii) lack of road edge. Construction errors can be the following: i) improperly compacted layers of earthworks, ii) levee materials built-in at high water level.

3.2.3. Dike materials

As mentioned in the methodology section, the water directorates were asked about the material of the identified dike section. In 87.3 % of the cases with known soil type, the embankment (subgrade) material under the pavement was categorised as clay. If we consider silty and sandy clays, the percentage rises to 92.9 % of all the documented pavement crack cases. It is difficult to characterise a dike section with a single material, as dike parts might contain different layers due to continuous strengthening and raising. These layers are mainly clays and silts. In the territory of the North-Transdanubia Water Directorate (01.), the levees have a clay cover, but their core is less impervious.

Figure 12 shows the fill material under the pavement cracks, broken down by water directorates. In the Tisza valley, clays are found almost exclusively in the dike under the cracked pavement. However, in the western part of Hungary, silt was commonly used as a dike material. Furthermore, granular materials were also placed into the flood protection embankments.

Similarly to the previous result summaries, the dike material at the damaged pavement sections is given according to the two river basins in *Table 2*.

Table 2 Embankment material under the damaged pavement (number of sections)

Material of the embankment	Danube	Tisza	Σ
Clay	956	761*	1717
Silty clay	50	49	99
Sandy clay	7	16	23
Silt sandy clay	6	0	6
Silt	5	0	5
Sandy silt	81	0	81
Sandy clayey silt	8	0	8
Silty sandy gravel	21	0	21
Silty sand	4	0	4
Mine barren	0	3	3
No data	20	0	20
Σ	1158	829	1987

* in 7 cracked cross sections dispersive clays were identified.

Source: Illés–Nagy, 2022

Table 3 | Secondary causes of the crack and their direction

Crack direction, compared to the axis of the dike	All cases		Shrink. & swell		Vehicle load		Earthwork consolidation		Planning and construction flaws		No answer		Others	
	No.	[%]	No.	[%]	No.	[%]	No.	[%]	No.	[%]	No.	[%]	No.	[%]
Parallel	854	43	**169**	**55.2**	**318**	**46.3**	70	12.9	**139**	**82.7**	**95**	**56.9**	**63**	**53.8**
Perpendicular	671	33.8	22	7.2	199	29.0	**420**	**77.5**	4	2.4	6	3.6	20	17.1
Parallel + perpendicular	297	14.9	85	27.8	115	16.7	35	6.5	15	8.9	34	20.4	13	11.1
Winding	50	2.5	24	7.8	10	1.5	9	1.7	3	1.8	4	2.4	0	0.0
Undetermined	100	5	6	2.0	42	6.1	6	1.1	7	4.2	19	11.4	20	17.1
No data	15	0.8	0	0.0	3	0.4	2	0.4	0	0.0	9	5.4	1	0.9
Sum	1987		306		687		542		168		167		117	

Own source

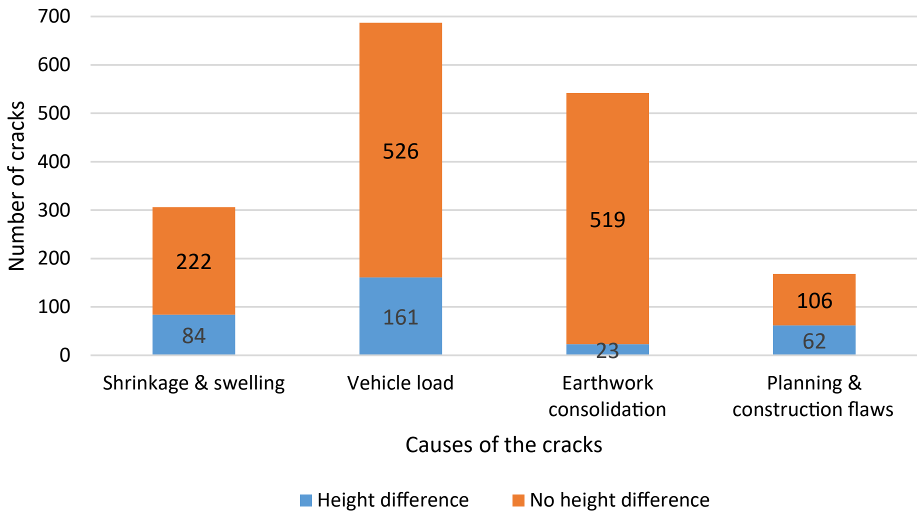

Figure 13 | Causes of the pavement cracks and number of cracks in each group with a height difference

Own source

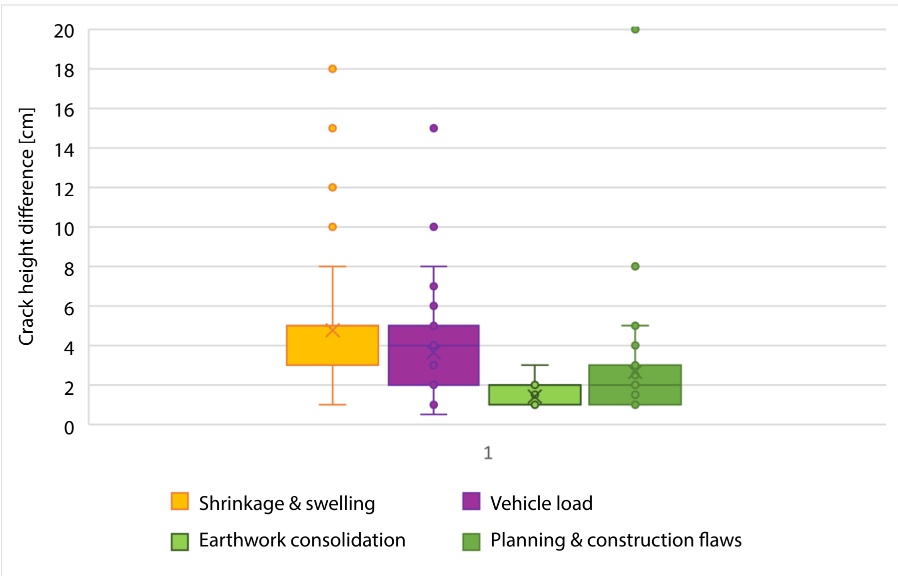

Figure 14 | Crack height difference in the case of the four most important secondary causes

Own source

3.2.4. Crack direction – shrink-swell as a cause

In 304 cases, out of the total 1,987, swelling and shrinkage were reported as the secondary cause of crack formation. In those cases, 55.2% of the cracks were parallel to the axis of the embankment, and 83.0% of the crack patterns observed had parallel fissure components. In the whole data set, 43% of the cracks were parallel with the axis of the embankment (see *Table 3).*

Not just the orientation of the crack but also the height difference between the two sides of it was documented as an indication of uneven settlement or heave. *Figure 13* shows the number of cracks with height differences among the four major secondary causes of fissure formation. *Figure 14* indicates the height difference distribution of these cracks, marked by the box plots.

4. Discussion

The security aspects of the flood protection embankment desiccation are not fully understood. According to the literature, no dike failure occurred in the Carpathian Basin and in the current day Hungary after it was weakened by drying *(Nagy 2006, 2018, 2022)*. There is a 4.8% pie slice where the failure mechanism was deterioration. This can also include consequences of desiccation.

The failure mechanisms were proposed by *Dyer–Utili–Zielinski (2009)*. It is based on his investigations and on the work of *Cooling–Marsland (1953),* who identified desiccation fissuring as a major contribution to embankment collapse during the 1953 North Sea flood. *Szepessy (1991)* described the appearance and evolvement of desiccation cracks in the case of dikes. The possible ways of embankment deterioration are also described. Altogether the causes are not linked directly to a failure mechanism.

A few authors state *(Antal–Hornyacsek 2015; Nagy 2022)* that flooding is Hungary's most significant natural hazard. I want to argue with that. Drought is becoming at least as big a problem as flooding. It is just enough to look at the primary causes of dike pavement fissuring (see *Figures 9* and *10*). The first seven months of 2022 were one of the driest periods in the country's history. Droughts will continue to be a source of problems in the 21st century.

According to the SWOT analysis of the main flood protection structures conducted by *Antal–Hornyacsek (2015),* ageing and deterioration were mentioned among the main factors that threat the stability of dikes. In this context, shrinkage, swelling, and desiccation cracks contribute directly to deterioration.

The probabilistic design method in the case of dikes was raised by *Nagy (2008)*. *Kádár–Nagy (2017)* examined the uncertainties of the shear strength parameters of the soils and their effect on the factor of safety and failure probability. These uncertainties increase further at the desiccated zone of the dike.

5. Conclusion

The survey presented in this paper is the most extensive one dealing with the fissures of paved dike crest as regards to the size of the covered area (territory of Hungary), length of dikes (1,250 km), and the number of identified sections: 1,987. The General Water Directorate (OVF) of Hungary requested the territorial water directorates to conducted the survey. The documentation of the cracks include: their location, direction, pavement type of the embankment, dike construction material and probable cause. As an evidence, the cracks were documented with photo(s).

Primary and secondary causes of crack formation were defined. The primary effects were: floods, droughts and consolidation, while secondary causes were mainly material properties (swell-shrink, dispersivity) and human causes (vehicle load, planning and construction flaws). These are interlinked, the consequences of one another (flood + vehicle load, drought + swelling and shrinkage properties, see *Figures 10–11.*

The spatial properties of the cracks can indicate the secondary cause up to some extent. Pavement above clay layers with volume variable property tends to exhibit cracks with longitudinal component 83% (see *Table 3*, parallel 55.2%, parallel + perpendicular 27.8%).

In the case of vehicle load the cracks appear parallel (43%) and parallel + perpendicular (29%) with the axis of the dike. Their height difference is less than in the case of volume variable clays.

Earthwork consolidation exhibits cracks perpendicular to the axis of the dike with little height difference between the edges of the fissures.

Planning and construction flaws are indicated mainly by longitudinal cracks as the cross rigidity of the pavement layers is insufficient, and the sides of the pavement often are not supported.

It is challenging to distinguish the cause of the crack by its appearance, as primary and secondary causes overlap. There can be more secondary causes as well.

Acknowledgement

The author would like to acknowledge the work of the Területi Vízügyi Igazgatóságok (Territorial Water Directorates) for executing the survey and the support of the Országos Vízügyi Főigazgatóság (General Directorate of Water Management – OVF). The author would also like to acknowledge the help of the PhD supervisors László Nagy PhD (BME), and Örs Antal PhD

(OVF). Moreover, the author is grateful for the help of his colleagues at OVF, especially Anita Süveggyártó, who helped with map drafting in ArcGIS software. Figure 4 was enhanced by Liza Gunzinám (landscape architect).

Project no. 1022641 has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the KDP-2020 funding scheme.

NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE
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PROJECT FINANCED
FROM THE NRDI FUND

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