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Effect of climate change on earthworks of infrastructure: statistical evaluation of the cause of dike pavement cracks

Zsombor Illés[1,2*] and László Nagy[1]

Abstract

The flood protection embankments of Hungary and Europe face numerous challenges. Some dike bases were constructed more than 200 years ago; since then, they have been elevated and extended. Because of these iterative adaptations, the dikes bear many construction errors, which can trigger failures and slides. Due to climate change, droughts and low-water periods of the rivers in central Europe are becoming more frequent. As a result of these effects, 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 General Directorate of Water Management ordered a comprehensive survey of dike pavement cracks in Hungary. This was one of the most extensive surveys of such kind. Hungary has some 4400 km of primary flood protection embankments, out of which 1250 km is paved. There are multiple reasons why the pavement of an embankment can crack. The main features of crack patterns related to clays with shrink-swell potential are identified. The results of international studies and the present survey are synthesised. The main objective of this paper is to draw a correlation between drought (aridity) zones, plasticity index of the soil samples, and crack thickness.

Keywords Effect of climate change, Pavement crack survey, Dikes, Swelling-shrinking, Clays

Introduction

Climate change influences and endangers earthworks of infrastructure. Due to the higher temperatures worldwide, the increased evaporation leads to desiccation and fissuring. The uneven rainfall patterns do not balance the moisture content of the embankments. The material selected for their construction, decades or a hundred years ago, also contributes to fissuring. At that time, research in the field of the shrink-swell capacity of clays was limited. One of the earliest examples of such was done by Kindle (1917), who examined the formation of 'mud-crack' in two different clays under different drying conditions. The research was accelerated in the second half of the twentieth century when desiccation polygons and cracks were widely observed on the surface of many natural and artificial formations such as dried lake beds, playas in the USA and in Australia (Neal 1968).

By that time, a considerable length of the Carpathian Basin's flood protection system was already built. Another 40 years passed until the volume variable properties of the clays used in Hungary for the construction came into insight. The Carpathian Basin is more exposed to the effects of climate change than most European regions (Hungary Today 2021). In the past 120 years, the warming reached 1.2 °C in Hungary, according to the Hungarian Meteorological Service (OMSZ), while globally stayed at 1.1 °C. The droughts of 2022 in Hungary are unprecedented; fish ponds are drying out. Due to climate

*Correspondence:
Zsombor Illés
zsombor.illes@edu.bme.hu
[1] Department of Engineering Geology and Geotechnics, Faculty of Civil Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, Budapest 1111, Hungary
[2] General Directorate of Water Management, Flood Protection Department, Márvány utca 1, Budapest 1012, Hungary

change, the region's moderate continental climate is shifting towards Mediterranean weather conditions. Periods of high temperature 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 and 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. One indicator of climate change is the more frequent and more extreme rainfalls. Their spatial and time distribution is uneven (Kocsis 2018). The days with high precipitation (above 20 mm) decreased during the second half of the twentieth century. However, in the past two decades, years with the most days of high precipitation have been recorded (Kocsis 2018), heavy rainfalls have the potential to cause flash floods (EEA 2012).

This article describes a survey that was conducted on the paved dikes of Hungary. The length of the paved primary flood protection system is 1250 km long. The pavement cracks are an indication of the deterioration of the pavement and deterioration of the earthwork itself. This survey marks an important step as it serves as a baseline for further crack surveys in Hungary. Due to the scale and the results, it is valuable for researchers all over the world. The research presented in the current article fits into several studies dealing with the effect of climate change on earth embankments (Vardon 2015; Tang et al. 2018; Pk et al. 2021).

At first, the article summarises the causes of desiccation, the state of the flood defence system assessed, and the climatic effects the earthworks face. Previous stability surveys in Hungary and pavement crack surveys from Texas, the USA, the Netherlands and Saudi Arabia are reviewed. The methodology of the pavement crack survey is presented, followed by the inspection results and the outcome of previous soil mechanical investigations of the damaged sections. The article discusses the effect of climate change, and finally, conclusions are drawn.

Causes of deterioration and dike surveys

The pavement cracks are an indicator of the deterioration of the pavement and deterioration of the earthwork itself. This section lists the root causes of environmental-induced deterioration, such as the more arid climate and construction errors. To explore these causes, surveys have been conducted in Hungary and in other parts of the world, for example, Texas, the USA (Jouben 2014), the Netherlands (Chotkan 2021), and Saudi Arabia (Dafalla and Shamrani 2011). The outcome of these previous surveys is summarised in this chapter.

Impact of floods and droughts

Flood protection embankments can be damaged by the effects of extreme environmental phenomena such as floods and droughts. Floods can follow the snow melting or a rainy period, and flash floods sometimes follow rapid events. Due to floods, the levees are wetted to a different extent, depending on their materials. In the Carpathian Basin and on the territory of current-day Hungary, the two most common causes of dike failure were overtopping and hydraulic soil failures (Nagy 2006, 2008).

Due to climate change, flood risk may increase, so authorities have to define the acceptable flood risk (Thistlethwaite et al. 2018). Due to climate change, drought risk has also increased.

Drought is a rather complex natural phenomenon that, in many ways, can be characterised. According to Palmer (1965), drought can be considered a persistent and significant lack of precipitation. We can distinguish meteorological, agricultural, and hydrological droughts, which can vary in the relative extent, duration, spatial extent, and possible consequences of water scarcity. Different indices are used to characterise the different types of droughts (Niemeyer 2008). Palmer drought severity index (PDSI) (Palmer 1965) uses precipitation and temperature data. While the Standard Precipitation Index (SPI) (McKee et al. 1993) is a relatively new drought index based only on precipitation, favourable in regions with limited data access (Mekonen et al. 2020). Reconnaissance Drought Index (RDI) requires precipitation data and the calculation of potential evapotranspiration (Tsakiris and Vangelis 2005; Tsakiris et al. 2007).

The Pálfai Aridity Index (PAI) was developed in Hungary (Pálfai 1990; Pálfai 1991), it is more complex than PDSI and SPI. However, evapotranspiration, similarly to SPI, is not taken into account. This limits the ability of PAI and SPI to capture the effect of increased temperatures (linked to climate change) on moisture demand and availability. It is an agricultural drought index and considers many aspects of water scarcity, such as: i) the number of extreme heat days (average temperature is above 30 °C), ii) length of low rainfall periods, and iii) depth of the groundwater table. The above-listed factors modify the following ratio:

$$PAI = \frac{100 \cdot Apr. - Aug.(med.temp.)}{Sept. - Aug.(precipitation)} \quad (1)$$

As aridity indices (including PAI) are developed mainly for agricultural purposes, in the case of the precipitation values, they are weighted according to the time-varying water requirements of the plants.

A drought and water scarcity monitoring system was established in Hungary. It has more than 150 operational monitoring stations. At the stations, meteorological parameters and the soil's water content are measured at different depths: 10, 20, 30, 45, 60 75 cm (Fiala et al. 2018; Drought monitoring). These stations provide real-time aridity and water scarcity value, which is essential for agronomists.

In case of floods and droughts, the national water management body distinguishes the following preparations (lowest to highest): no preparation, grade I., grade II., grade III. and extreme level. The drought levels are defined by the Hungarian Drought Index (HDI). It is based on meteorological data and the soil moisture content of the top 80 cm soil layer, data is coming from the drought monitoring stations. It is a soil-specific index, considering the soil's water management properties.

Dike system of Hungary

During the nineteenth century, the river regulations transformed the slow-flowing meandering Tisza river into a waterway that could be used for transportation. In the meantime, most of its flood plains were reclaimed for agricultural use. The Carpathian Basin has approximately 11 000 km of flood protection embankments. Out of that, 4900 km is located in Hungary, according to the General Directorate of Water Management (OVF). Most of the dike system is made of cohesive soils, roughly 4200 km, and a considerable length of these embankments are constructed of high plasticity clays ($I_p > 30\%$) (EN ISO 14688-2:2017).

The embankments are mainly built from local materials, namely clay, peat, silt and sand, using historic construction methods (Dyer et al. 2009). The term cross transportation was used for it; usually, the material is extracted from ditches at the waterfront. The construction of the dike system in Hungary began with river regulation in the nineteenth century, and since then, it has been developed (Nagy 2006). The layers created by the raising and strengthening of the dikes are visible in Fig. 1. The layered structure is regarded as an 'onion shell'; typical cross sections of the Tisza and its tributary rivers' embankments are presented in Tóth and Nagy (2006) and Schweitzer (2009). The embankments are inhomogeneous, the layers are usually made of different types of soils. The method of such dike construction contributes to the possibility of the following errors: i) certain layers are built from unsuitable earthwork materials, ii) due to inadequate compaction, the layers are not joined, iii) built-in cohesive soils with high water content, iv) unfavourable subsoil conditions (crossing of the previous river bed). One or more of the above-listed errors tend to occur at certain dike sections (Nagy 2000).

Clay minerals determine the physical and mechanical properties of the cohesive soils. So it is also essential to investigate soils' fine grain and mineralogical composition.

Clay minerals

Clays susceptible to volume change were used to construct the Hungarian dike system. They do not consider it a threat until the water content is relatively permanent. The clays shrink when the water content decreases, and desiccation cracks form.

The three-layered clay minerals (2:1 clay) consist of an octahedral sheet surrounded by two tetrahedral sheets such as illite, vermiculite and montmorillonite from the smectite group. Montmorillonite swells strongly due to

Fig. 1 Onion shell structure discovered during the relocation of a dike near, Fokorú-puszta (Tisza right bank, north of Szolnok) (authors illustration)

the presence of water, while vermiculite has a medium shrink-swell capacity. There are various ways, such as X-ray diffraction (XRD) and Differential Thermal Analysis (DTA), to determine the clay mineral composition of soils (Mitchell 1974).

According to the geological map of the great Hungarian Plain (Stefanovits and Dombovári 1985), there is ample, high plasticity, deformable clay near the surface, especially in the Tisza valley where the soils have a high smectite content. The flood protection embankments' swelling-shrinkage problem at the Tisza valley has been investigated for years (Szepessy 1991; Lazányi and Horváth 1997). The mineralogical composition of the clays analysed and compared in this article are presented in Table 1.

Models for crack development

Soil science designates clay soils, which shrink when drying and swell upon wetting, as vertisols. These soil types are widespread in Hungary (Fuchs et al. 2015). In the case of clay soils, the moisture transport based on hydraulic conductivity and water retention curve cannot be fully calculated as swelling and shrinkage result in the opening and closing of cracks. Shrinkage characteristics have to be introduced (Bronswijk 1988). Later on, Bronswijk (1991) conducted different field measurements to estimate the three-dimensional shrinkage of soils. A framework closer to the soil science approach was proposed by (Stewart et al. 2016). It connects three porosity domains i) aggregate, ii) shrinkage cracks and iii) subsidence.

A numerical study of soil–vegetation–atmosphere interaction was conducted to analyse the effect of root zone cracking, and precipitation on the flood protection embankments slope safety (Jamalinia et al. 2020, 2021). An essential finding of the mentioned research is that the leaf area index (LAI) can be used as an indicator of the health of the embankment.

Predictive models such as classification and regression trees (CART) can forecast the cracks' length and depth after identifying cracking indicators in a sample area and investigating their correlation (Chotkan 2021).

A framework based on the theory of linear elastic fracture mechanics (LEFM), which provides a mathematical description of the phenomenon of crack propagation, was introduced by (Konrad and Ayad 1997a). Data obtained during the experiments (Konrad and Ayad 1997b) was essential to validate the model.

Summary of the previous investigations

Apart from model development, it is also essential to conduct crack surveys, identify the causes leading to crack formation and monitor the crack propagation and closure. The following subsection summarises the large-scale subsoil surveys and dike stability analyses conducted in Hungary (Nagy 2000). Since then, the flood protection embankments crest was paved to ease transportation and surveillance. Visual inspections of dike crests (paved and unpaved), road pavement (asphalt) surveys coupled with soil mechanical investigations were conducted internationally. These inspections are reviewed in one of the forthcoming subsections.

Investigations in Hungary

By 1996, the stability survey of Hungary's 4200 km long dike system was completed. This survey comprises geo-electrical measurements, soil mechanical investigations and subsoil stability calculations built upon one another (Nagy 2000).

Table 1 Mineralogical composition of soils with shrink-swell behaviour

Minerals	Formula	USA, Texas, Taylor (Arthur O. 1964) Formation	Dutch, River Clay (Tollenaar et al. 2017)	Portugal, river Tejo, clay	Hungary, Körös river dike
Quartz	SiO_2	20	50.2	43	30
Mikroklin	$KAlSi_3O_8$	–	–	20	3
Albite	$NaAlSi_3O_8$	–	–	8	8
Montmorillonite	$(Na,Ca)(Al,Mg)_2[Si_4O_{10}(OH)_2]\cdot H_2O$	50	–	5	45
Chlorite	$Mg_5Al(Si_3Al)O_{10}(OH)_8$	–	–	8	8
Illite	$(K,H_3O^+)(Al,Mg,Fe)_2[(Si,Al)_4O_{10}(OH)_2\cdot(H_2O)]$	8	–	7	6
Calcite	$CaCO_3$	10	5.8	2	–
Anorthite	$Ca(Al_2Si_2O_8)$	–	6.8	–	–
Dolomite	$(Ca,Mg)(CO_3)_2$	–	–	2	–
Muscovite	$KAl_2[AlSi_3O_{10}(OH)_2]$	–	16.2	5	–
Kaolinite	$Al_2O_3\cdot 2SiO_2\cdot 2H_2O$	8	–	–	–
Vermiculite	$(Mg,Fe,Al)_3((Al,Si)_4O_{10})(OH)_2.4H_2O$	–	21	–	–

Conventional (trench) sampling and non-destructive (geophysical) measurements were used to track the possible depth and extent of desiccation cracks. At that time (1990–1996), a smaller portion of the flood defence embankments crest was paved, and cracks were less noticeable on the grassy and plain surfaces. Most stability survey sampling and measurements occurred on Tisza's river embankments surrounding the main river bed and the oxbow lakes (Salát and Nagy 2002).

The application of different geotechnical drilling and geophysical measurements during the dike surveys in Hungary and other parts of Europe are summarised in Table 2.

International pavement surveys

It is rare to conduct extensive field surveys on pavement cracks. There are very few international surveys usually focusing on a smaller region. The general belief that pavement cracks appear due to heavy traffic leads to the lack of these surveys. However, the pavement of low-volume traffic roads can also become fissured. The rapture of the pavement can be caused by the volumetric strains induced by the swelling and shrinkage cycles of the subgrade soil. It has been observed that longitudinal cracks develop during the dry season in Central Texas, USA (Jouben 2014). In that study, 20 road sections were selected from the area where expansive soils were presumed in the subgrade. The cross-sections were documented with photos, and undisturbed samples were collected from depths ranging from 0.6 to 3.0 m. Forced ventilated swell-shrink tests were conducted on specimens from six specific cross-sections of roads. This type of test was developed and used at the University of Texas, Austin. It can be conducted on undisturbed or remoulded samples. The specimen is swelled (wetted) and then consolidated (and dried) under field loading. The drying process was accelerated by forced ventilation. This practical test method allows the engineers to determine the correlation between vertical movement and water content (Jouben 2014).

Dafalla and Shamrani (2011), near Al Ghat, Saudi Arabia, identified six types of pavement cracks related to swelling and shrinking soils. From those, four types are also present on the paved dikes of Hungary. These were the following: i) transverse cracks, ii) longitudinal cracks, iii) block cracks and iv) yield (alligator) cracks. Block cracks are visible in Fig. 4. they are larger, well-defined pieces, usually caused by desiccation, while yield cracks are parallel or interconnecting crack patterns evolving due to the bending or horizontal movement of the asphalt (Fig. 6 iii). During the Hungarian survey evaluation, these two types of cracks were considered as crack systems of transverse and longitudinal cracks.

While the first two mentioned surveys dealt with paved roads, the third one (Chotkan 2021) describes a regional dike survey of Delfland, Netherlands (some of the dikes were paved, but most of them were covered with grass). A data set of more than 1000 crack observations were analysed. The volume variable property of the soils is induced by the change in water content caused by droughts and floods.

Methodology

The General Directorate of Water Management (OVF) ordered a comprehensive nationwide crack survey of the paved surfaces of flood protection embankments in 2018. The survey was conducted by 12 territorial water directorates and supervised by the General Water Directorate. The scale of the survey is unprecedented in Hungary as well as in Europe. According to our knowledge, similar surveys, somewhat smaller in scale, were made in Saudi Arabia, concentrated on the region of Al Ghatt (Dafalla and Shamrani 2011) and in Austin, Texas (Jouben 2014).

The reason for starting with pavement fissures is that they do not heal as easily as fissures on unpaved parts. The dike crest is paved for multiple reasons. The most outstanding is to ease the flood control operations. Inspections are more rapid and easier. Transport vehicles can move equipment faster and safer during flood protection operations. The pavement material in examined sections is as follows: 94.8% asphalt, 2.4% concrete cover and 2.8% sett.

Due to the viscous nature of the bitumen binder, asphalt can sustain significant deformation before the

Table 2 Application of geotechnical sampling and geophysical measurements

Purpose	Method	Publications
Water content distribution in a cross-section	Direct sampling	(Nagy 2010), (Nagy and Huszák 2012)
	Geoelectric cross-section	(Nagy 2000)
Identification of desiccation cracks and raptures	Georadar measurement	(Fauchard and Mériaux 2007; Nagy 2010)
	Saline solution pumping and electric resistivity tomography investigation	(Nagy et al. 2008; Jones et al. 2014; Kovács et al. 2020)
Water content distribution in the axis of an embankment	Longitudinal geoelectric section	(Fauchard and Mériaux 2007; Nagy and Huszák 2012)

crack comes into sight. This is an advantage from a maintenance point of view and a monitoring problem, as cracks appear on the crest with a delay. Paved dike crests have disadvantages as well: i) after long dry periods, the water cannot infiltrate into the dike body to normalise water content, ii) the rainfall runs off on the paved top surface and on the sides, iii) moisture is partially trapped after significant floods as there is no evaporation through the pavement. The asphalt or concrete layer acts as a water barrier and disturbs the water balance of the dike. In addition to the pavement's state, the dike material's knowledge is also essential to understand the section's behaviour and the reasons for deterioration.

Along with the pavement crack survey, the results of recent soil mechanical investigations were reviewed, and the soil parameters were collected. In the reviewed cross-sections, more than one layer of soil was usually encountered. The gathered data set was supplemented with the literature's soil parameters and desiccation crack patterns.

Dike pavement crack survey

The backbone of the research is the survey prepared and evaluated by the article's authors at the request of the General Water Directorate. Altogether 1250 km of paved flood protection embankment were inspected, and 1987 smaller or bigger fissures were detected, which means an average of 1.6 cracks/km.

The following characteristics were collected as a marker for this paper:

- Location of the crack(s) on the embankment (most of them appeared on the crest of the embankments, 97.6% 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 cause of the crack formation (floods and droughts).

The geometry, location and aspect of cracks were documented by photo(s). The same attributes were recorded by other surveys (Dafalla and Shamrani 2011; Jouben 2014; Chotkan 2021) in the case of paved and turf-covered dike crests.

Depending on the number of cracks, the extent (in m or m^2) of the fissured area indicates the spatial spread of the issue, such as soil layer susceptible to volume change, weak asphalt layers and the need for maintenance. Crack thickness combined with the extent can indicate the seriousness of the fissure since a few meters long, thick crack (an indication of a few ten-centimetre deep penetrations) can cause strength reduction in the soil layer and by that affecting the slope stability. The Delfland Water Board has a policy that cracks longer than 2 m or deeper than 50 cm are considered as dangerous and should be repaired (Chotkan 2021).

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 (1–12),
- 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.

Database of soil mechanical investigations

The authors assembled the database of soil mechanical investigations from recent soil explorations. In these investigations, samples were collected from approximately 30 locations, signs of swelling and shrinkage, cracks with height differences on the pavement and desiccation fissure patterns on the slopes were observed. From these sections, 114 samples at different depths were taken. The locations are marked in Fig. 13. Since most of the soils used for embankment construction are cohesive, apart from soil identification (Atterberg limits, based on ISO/TS 17,892-12:2004), shrinkage parameters such as linear shrinkage were also determined in some cases. One of the most common ways to describe a soil's volume change capability is swelling potential, defined as the percentage of the swell of a confined sample in an oedometer test soaked under a surcharge load of 7 kPa. The swelling potential is linked to:

- Atterberg limits,

- Linear shrinkage,
- Colloid content,
- Activity index,
- Swelling index.

From the soil mechanical part, the publication focuses on the correlations between swelling potential and Atterberg limits, as it is the most widely measured soil parameter in the case of cohesive soils.

Results

In this section, the results of the pavement crack survey and the gathered data set of soil mechanical investigations are evaluated separately and together. Results in correlation with floods and droughst are also presented.

Pavement crack characteristics

According to the methodology described in the previous section Table 3 summarises the number of cracks and the length of the cracked embankments. The values are presented separately for the Danube and the Tisza catchment areas. The behaviour of the floods, the embankment materials and their height also differ in these regions. Besides the number and length of cracked pavement, the length of paved flood protection embankments managed in the areas, and the specific number and length of cracks are also shown in Table 3.

The system of flood control embankments in the Tisza catchment area is generally higher and longer than in the Danube region. However, there are fewer, but longer cracks on the dam crests in the Eastern part of Hungary (i.e. where the Tisza and its catchment area is 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.

Location of the crack(s)

The width of road pavement is approximately 3 m. It is divided into three strips, each of them with 1 m width according to the schematic picture presented in Fig. 2. After the evaluation of the pictures and the received answers, the decision was made that the crack appearance was classified into the following groups: i) fractured sides, ii) cracked axis, and iii) fissures throughout the cross-section. No difference was made regarding classifying the cracks that appeared 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. During the past decade, a series of emergency flood retention reservoirs were constructed along the Tisza River in Hungary.

The whole paved cross-section is considered fissured if cracks are visible on the central strip and either side strip (Fig. 2). This consideration may lead to the fact that the entire cross-section is fissured in more than half of the cases, as presented in Fig. 3.

Fig. 2 Position of fissures on the paved dam crest

Table 3 Number and length of pavement cracks at the catchment area of the Danube and Tisza

Catchment area	[-]	Danube	Tisza
No. of cracks	pc	1158	829
Length of cracked pavement	m	31,960	247,704
Length of paved dikes	km	360	890
Specific number of cracks	pc/km	3.22	0.93
Specific cracks	m/km	8878	278.32
Average dam height	m	3.20	3.78

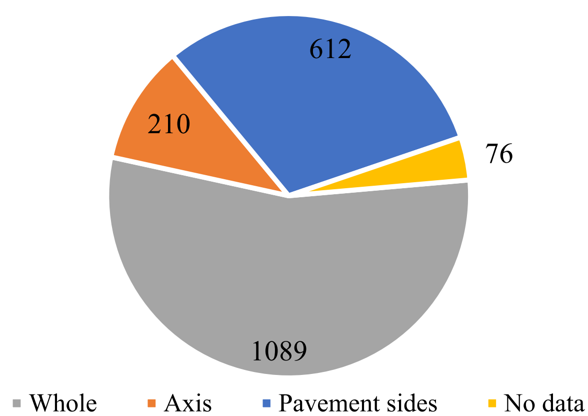

Fig. 3 Summation on the location of cracks at the paved cross section

Fig. 4 Crack direction compared to the axis of the embankment

Orientation of the crack(s)

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 Fig. 4. 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. The ratio of categories is shown in Fig. 5.

Pavement crack thickness

An arbitrary crack thickness classification was created with the following categories: i) thin, ii) medium and iii) thick. Thin and medium cracks indicate an issue with

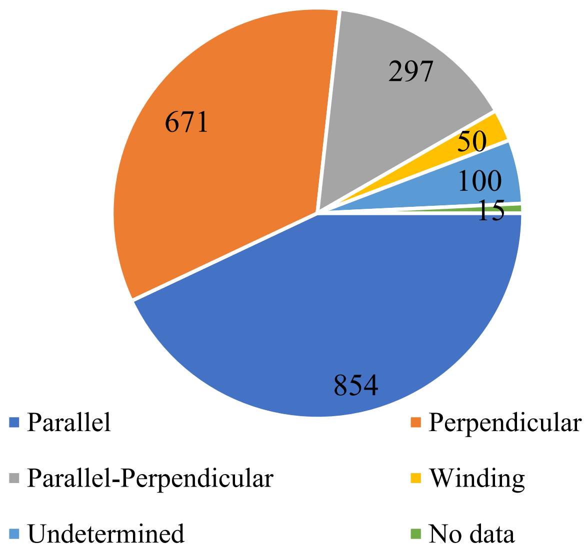

Fig. 5 Proportion of crack directions

the pavement or with the sublayers (pavement work gap, heavy traffic). However, thick cracks (> 5 mm) often coupled with pavement deflection (Jouben 2014) suggest problems of the embankment material, which can be the volume change capability of a clay layer in it. 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. The surveyors measured the thickness, directly categorised or approximated from the photos. The crack width categories are demonstrated in Fig. 6, and their ratio is presented in Fig. 7.

Reason of the crack formation – signs of shrink-swell soil

In the survey sent to the water directorates, we enquired about why cracks formed on the paved surfaces. Prior knowledge of the surveyors was essential in this question. The most common problem with 38% was traffic load; although half of these answers come from a single water directorate, it was followed by a lack of consolidation time (28%), which can be easily calculated. The three other categories that also scored 10% are; construction and design shortcomings, swelling and desiccation, and unknown causes. As this article focuses on deterioration caused by shrink-swell soil, this phenomen and the crack layout are correlated.

In 197 cases, out of the total 1987, swelling and shrinkage were reported as the leading cause. In those cases, 65.5% of the cracks were parallel to the axis of the embankment, and 85% of the crack patterns observed had parallel fissures. In the whole data set, less than 50%

i) Thin (Hairline) Tisza, left bank, 0+690 **ii) Medium** Tisza, right bank, 7+230 **iii) Thick (sturdy)** Tisza, right bank, 126+260

Fig. 6 Crack width; thin (1–2 mm), medium (2–5 mm) and thick (> 5 mm)

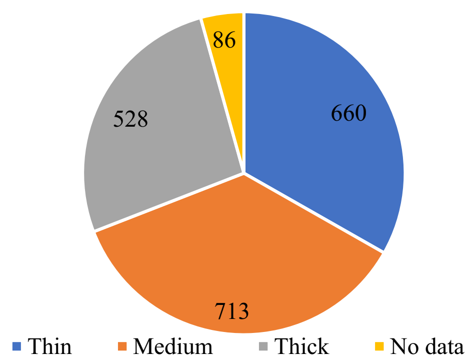

Fig. 7 Summation of each crack width category

Table 4 Percentage of crack patterns, all cases and cases of shrinkage and swelling

	All cases		Shrink. & swell	
Crack direction	**No.**	**[%]**	**No.**	**[%]**
Parallel	854	43.0	129	65.5
Perpendicular	671	33.8	22	11.2
Parallel-perpendicular	297	14.9	32	16.2
winding	50	2.5	8	4.1
Undetermined	100	5.0	6	3.0
No data	15	0.8	0	0.0
Sum	1987		197	

of the cracks were parallel with the axis of the embankment Tables 4.

Dike materials

Cohesive soils have the potential peril of swelling-shrinkage capability. In 87.3% of the cases when the soil type was known, the embankment (subgrade) material under the pavement was categorised as clay.

If we consider silty and sandy clays as well, the percentage rises to 92.9% of all the documented pavement crack cases. Dike sections might contain different layers, mainly clays and silts. It is not so easy to characterise a dike with a single material. In the territory of the North-Transdanubia Water Directorate (01.), the levees have a clay cover, but their core is less impervious. The material of the dike section under the pavement cracks is summarised for the two river basins in Table 5. The territorial water directorates indicated the type of soil under the sections with the fissured pavement. The ratio of the not fully clay embankments is presented in Fig. 8.

Clays prone to volume change were identified by the crack patterns and dispersive clays (saline soils) by signs of erosion. They are susceptible to tunnel erosion, causing damage to infrastructural facilities, mainly to dikes. The identification (by pinhole test) and treatment of dispersive clays have been researched from the ’70 s until today (Sherard et al. 1976; Nagy et al. 2015). Saline soils can be identified by their physico-chemical composition (Nagy et al. 2016).

Results of the soil investigations

There are different criteria to evaluate swelling potential: Peck et al. (1974) and Bowles (1996) consider the Plasticity index (I_p), as presented in Table 6, while others only consider the Liquid limit (w_L) (Dakshanamurthy and Raman 1973; Kay 1990) (Table 7), there are evaluation methods when both limits are considered (Pitts 1985; Kalantari 1991).

Histograms of the Liquid limit and Plasticity alongside their swelling potential are presented in Figs. 9 and 10. The statistical parameters, such as; means, standard deviation and coefficient of variation, of Atterberg limits are summarised in Table 8.

Atterberg limits of the soil sample data set (places with desiccation cracks) along with the samples available in the literature are presented on the Plasticity chart (Fig. 11). It is difficult to compare samples from different places. In Hungary, linear shrinkage is used to evaluate shrinkage properties, while in the USA, clay activity (Skempton 1953), which is the fraction of plasticity index and the clay fraction and shrinkage limit, is also a common index number.

Two paved cross-sections are chosen as examples (Fig. 12), where detailed soil investigations and photo documentation are available. In these cases, soil layers high with swelling-shrinking potential were encountered.

The two selected sites were the following: the Tisza left bank 25+689 and right bank 126+160. In the first site, the dike serves as the earthwork for a secondary road; in the second case, many soil mechanical investigations were carried out in the section. The cracks are parallel to the road’s axis, a bit winding, and there is a height difference between the cracks’ sides. They are examples of desiccation cracks.

Results of environmental effects

The survey, which was sent to the Water Directorates, explicitly asked whether the crack and damage emergence could be connected to floods or droughts. In Table 9, the results are presented according to the catchment area of the two main rivers. In one-fourth of the case (500), the crack formation can be associated with floods. 361 out of the 500 affirmative answers come from a Water Directorate in the Danube valley.

Table 5 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

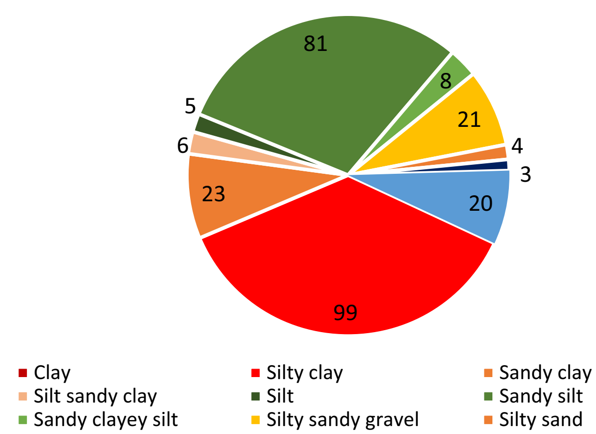

Fig. 8 Proportion of non-clay embankment material

According to the answers, in one-fifth of all cases (400), droughts played a role in the fissure and damage appearance. Most of the affirmative responses come from the Water Directorates operating in the Tisza valley, especially from the river's upper course. The survey shows that damage in the Danube valley is related to flooding while in the Tisza valley to drought.

Table 6 Plasticity index and swelling potential (Peck et al. 1974; Bowles 1996)

Plasticity Index (Ip)	Swelling potential	Percentage of samples [%]
< 15	Low	0.0
10–35	Medium	45.6
20–35	High	42.1
> 35	Very high	54.4

Table 7 Liquidity limit and swelling potential (Dakshanamurthy and Raman 1973)

Liquidity limit (w_L)	Swelling potential	Percentage of samples [%]
20–35	Low	1.8
35–50	Medium	13.2
50–70	High	59.6
> 70	Very high	25.4

Effects of aridity

According to PAI, Hungary's aridity zones are presented in Fig. 13; the dashed line is the border between the Danube (to the west) and the Tisza (to the east) catchment area. The two main rivers (Danube and Tisza) and their tributaries flow on the lowland, such as the Small Hungarian Plain and the Great Hungarian Plain. A considerable part of the dike system lies here. The documented cracks and the locations of soil mechanical investigations are also marked on the map (Fig. 13).

The driest region of Hungary is the Great Hungarian 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, which is more or less 28 000 km^2 (Pálfai 2004). During floods, excess water is not diverted and stored. Combined with the prolonged drought spells becoming more frequent due to climate change, the situation is even worse for the agricultural industry and the wetlands.

The connection of aridity zones and environmental effect such as: flood and drought is presented in Fig. 14.

According to Fig. 14, in heavy and extremely-heavy drought zones (I. & II.), floods and droughts are responsible for approximately 30% of the damage, while in zone III. it is much less because a large part of the Danube valley is included, where silty and sandy soils are present (see Table 5), so the dikes are less sensitive to the drought-induced shrinkage. Also, the lower course of the

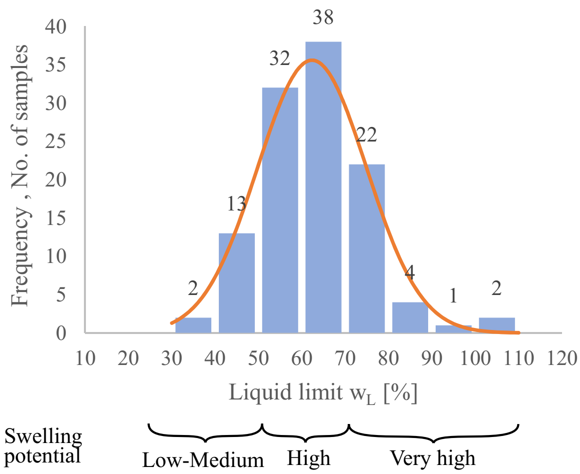

Fig. 9 Histogram of the samples Liquid limit (w_L) and swelling potential according to (Dakshanamurthy and Raman 1973)

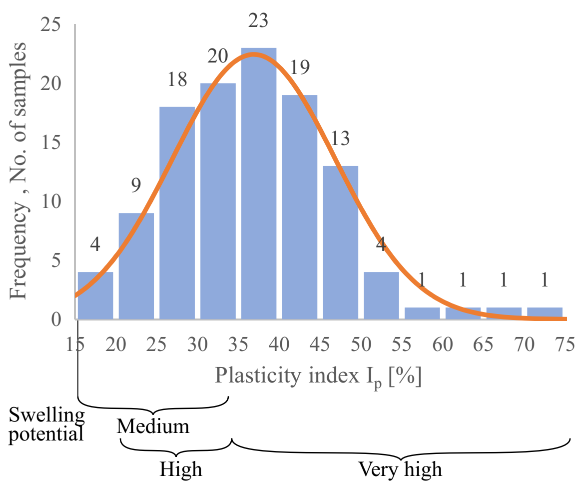

Fig. 10 Histogram of the samples Plasticity index (Ip) and swelling potential according to (Peck et al. 1974; Bowles 1996)

Table 8 Statistical parameters of the Atterberg limits (114 samples)

		L.l. (w_L)	P.l. (w_P)	P.I. (I_p)
Mean	μ	62.35	25.48	36.88
StD	σ	12.557	3.553	9.953
CoV		0.201	0.139	0.270

Danube is in this zone, where floods put a more significant pressure. In the case of the moderate-drought zone (IV.) the drought spells are responsible for roughly 25% of the damage. A considerable part of the Little Hungarian Plain is included, where the soil composition is different, and the appearance of high and very high plasticity clays is less likely. On the other hand, the north-eastern corner of the country falls into this zone, where the Tisza river enters. There the clays have an expansive behaviour, and the dikes retain water for a shorter course, so the cause shifts towards drought again. The embankments in aridity zone V. do not hold floods for a long time. The pavement is scraped by other means. There is no direct relation between the aridity zones and the desiccation crack formation, so other factors probably play a significant role.

Aridity index (PAI), soil plasticity and possible crack pavement crack formation

The layers' order and thickness can affect the resulting cracks, as well as the aridity zone and other factors such as i) the distance from the river, ii) frequency of inundation, iii) flood characteristics, depth of wetting, iv) orientation and v) nearby vegetation. It is difficult to characterise these five factors, so we would stay with the embankment's material (cohesive soil) and the aridity zones (according to PAI) and correlate these factors with the thickness of the cracks.

At 19 dike sections, approximately 45 drillings were deepened, and 114 samples (Fig. 11) were supplemented with ones where no signs of pavement fissure were visible (negative samples). The extended database comprises more than 160 samples (sections with cracked and uncracked pavement).

The most determinate layers are added to each section and drillings list. By determinate layer, it was meant that a medium plasticity clay would determine the dike section's shrink-swell behaviour in case of a silty clay embankment. In the same manner, in the case of a medium plasticity section, high or very high plasticity layers govern the volume change potential.

A Matrix was created (Fig. 15), drought (aridity zones) on the horizontal axis, while the samples were categorised by their liquid limit into; low to very high plasticity soil, and their plasticity index is presented on the vertical axis. The observed crack width is mentioned in each zone, according to Fig. 6.

The spread, locality and skewness of the plasticity index in the case of each group, if there is a sufficient number of samples, is demonstrated by a box plot (Fig. 15).

At places of the most severe drought (Zone I.) the crack width increases with the plasticity of the materials. The same trend was not captured in the case of drought zone II., as there were only a few samples of medium and low plasticity soils from Texas (Jouben 2014). In the case of drought zones III. and IV. (medium and moderate) dikes

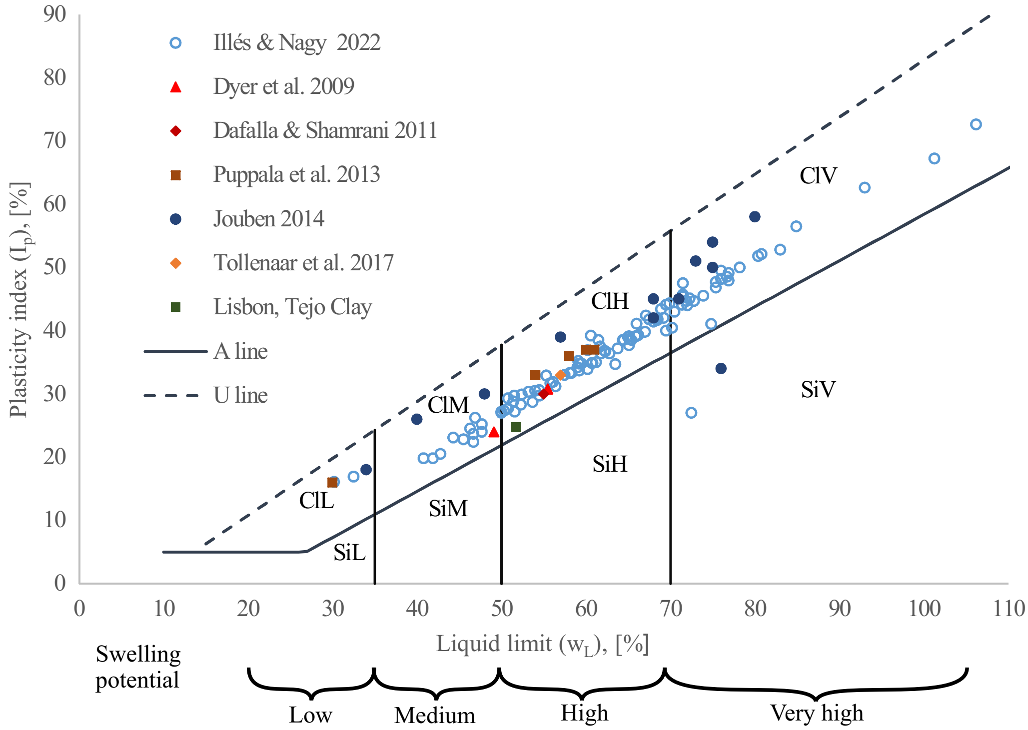

Fig. 11 Plasticity chart after Casagrande, according to ISO 14688-2:2017, samples from investigations: Dyer et al. 2009; Dafalla and Shamrani 2011; Puppala et al. 2013; Jouben 2014; Tollenaar et al. 2017, are marked

Tisza	Left bank 25+689	Right bank 126+160
Liquid limit (W_L) [%]	46,33	65,4
Plasticity index (I_p) [%]	25,73	38,5
Linear Shrinkage [%]	-	14,8

Fig. 12 Pavement fissures caused by shrinkage and swelling

Table 9 Crack appearance connection to flood and drought

Connection to	Catchment area		
Flood	Danube	Tisza	Σ
Yes	361	139	500
No	797	667	1464
Na data	0	23	23
Σ	1158	829	1987
Drought			
Yes	12	388	400
No	1146	424	1570
Na data	0	17	17
Σ	1158	829	1987

with very high plasticity soils tend to exhibit all kinds of pavement cracks, while other groups only have thinner fissures. No pavement cracks were observed in the mild drought zone (V.). Only unpaved embankments (results of Dyer et al. 2009) exhibited fissure patterns.

Discussion

The pavement crack survey showed statistically that crack patterns associated with swelling and shrinkage of dike material contain predominantly longitudinal cracks. Zornberg and Gupta (2009) and Jouben (2014) also concluded that longitudinal cracks are associated with expansive clay subgrade. On the other hand, Dafalla and Shamrani (2011) associated six different pavement crack types with expansive clays.

The pavement crack patterns associated with swelling-shrinkage dike material are linked to the Tisza catchment area, where the soils are rich in montmorillonite and other smectite minerals (Stefanovits and Dombovári 1985; Lazányi and Horváth 1997).

However, it is not only the embankment material that affects the crack extent. A correlation matrix was created between aridity, soil plasticity and crack width to prove this. These properties were chosen because they can be easily quantified. When there were enough samples from the same drought zone, it was clear that crack width increased with plasticity. In less severe drought zones, there were fewer or no pavement cracks on the analysed sections. For the analysis, mainly samples from Hungary were taken into account along with the result of the following studies: Dyer et al. 2009; Dafalla and Shamrani 2011; Puppala et al. 2013; Jouben 2014; Tollenaar et al. 2017.

Due to climate change, it will be even more critical to quantify droughts. Pálfai Aridity Index was used in this research as it can be easily calculated. It would be advised to use a drought index, which takes into account soil moisture such as HDI. The state of the vegetation, especially soft stem plants, can indicate soil moisture content in

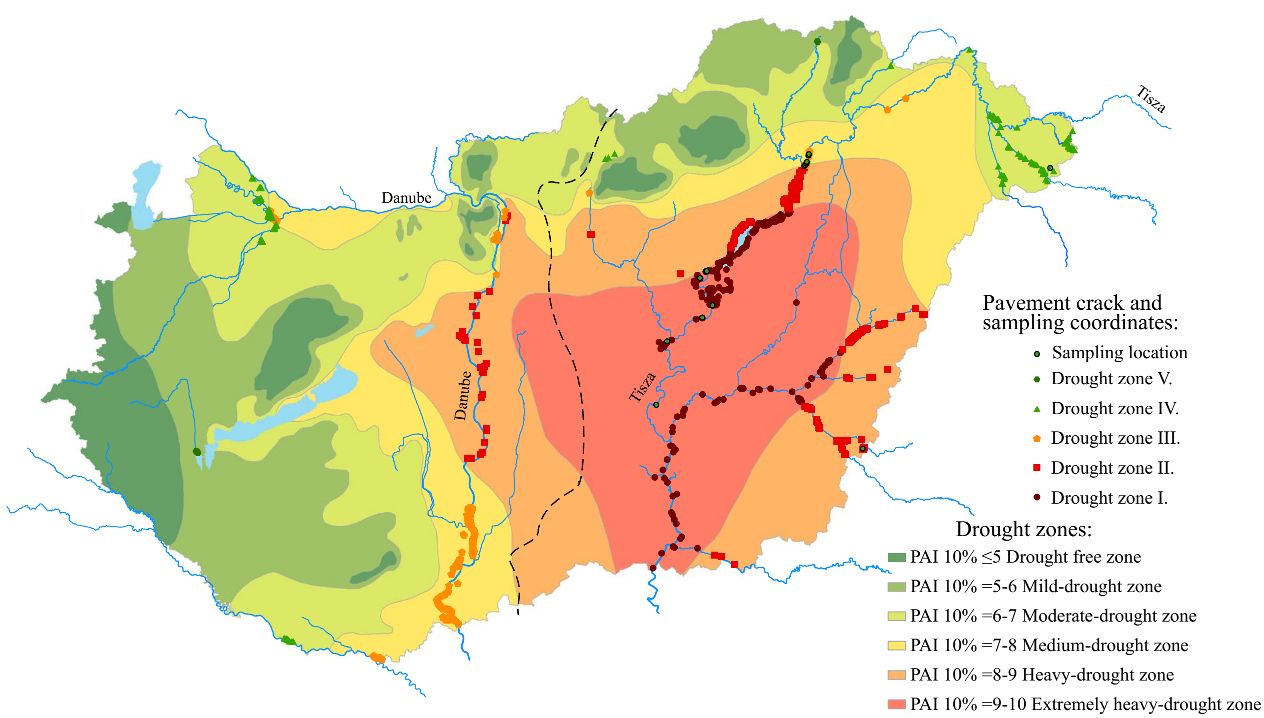

Fig. 13 Aridity map of Hungary (provided by OVF) and the coordinates of the pavement cracks presented

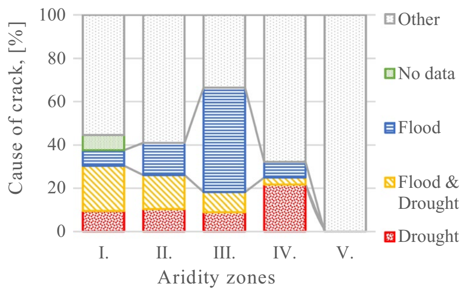

Fig. 14 Aridity zones and causes of cracks

embankments. The leaf area index (LAI) can be used as an indicator of the health of the dike (Jamalinia et al. 2020).

As a result of climate change, the earthworks of infrastructure desiccate occasionally even beyond repair. It is important to monitor the moisture content of the embankments and the crack propagation, as already done by: Utili et al. (2015); Yu et al. (2021).

Conclusions

The survey presented in this paper is the most extensive inspection of fissures on paved flood protection embankments regarding the size of the covered area (territory of Hungary), length of dikes (1250 km), and the number of identified sections: 1987. Upon request of the General Water Directorate of Hungary, the territorial water directorates conducted the survey. The encountered cracks, their location, direction, pavement type of the embankment, dike construction material and probable cause were collected, and the cracks were documented with photo(s).

The gathered soil property data set, augmented with the available data from the literature, were analysed along the crack survey. They show that dike materials and pavement crack patterns correlate. In the case of high plasticity and very high plasticity clays, which have a high swelling potential, predominantly desiccation crack patterns were observed. 85% of cracks connected to shrinkage and swelling had a longitudinal component.

In regions with heavy drought, the deterioration of flood protection embankments caused by desiccation can be as relevant as the damage caused by floods (see Fig. 14).

When aridity (heavy and very heavy drought zones I. and II.) is associated with a reach swelling embankment material and high plasticity soils, the desiccation fissures are more pronounced. This observation is supported by the cases documented in Hungary and by the results of studies made in other countries and regions (see Fig. 15).

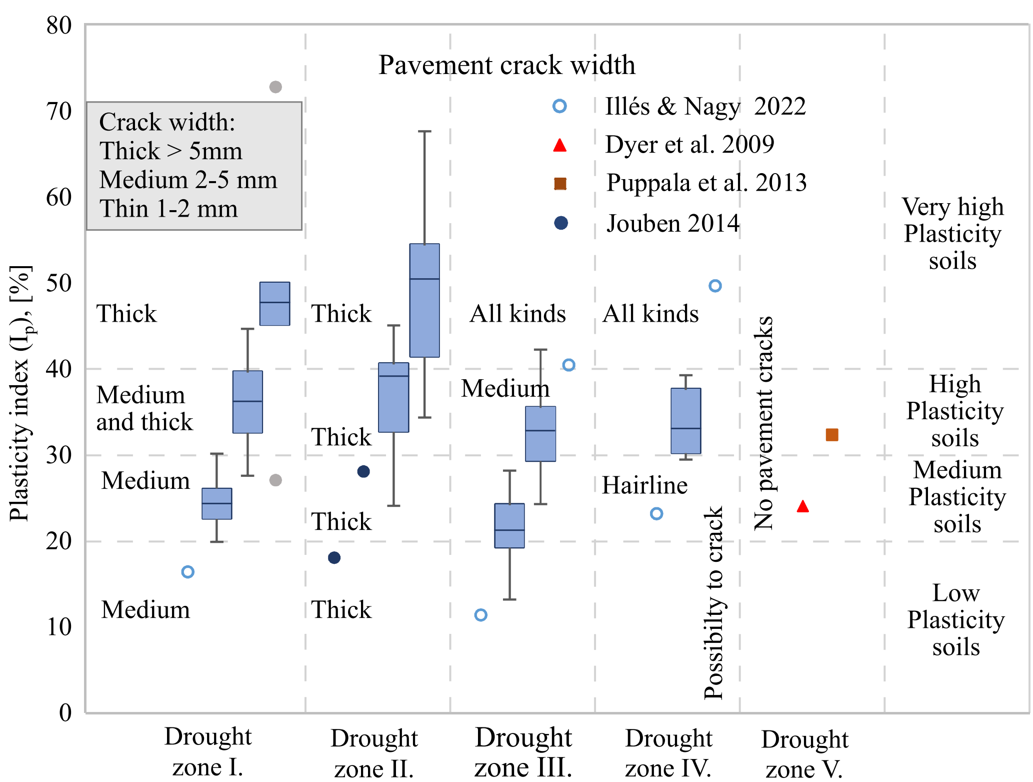

Fig. 15 Drought zones (I. to V.), soil plasticity of the embankment and pavement cracks

As a general statement, if the embankment has one meter thick high or very high plasticity clay acts as a determinate layer, the formation of pavement cracks is more or less inevitable. If the flood protection embankment is constructed of low and medium plasticity clay layers and some silty layers, preferably one below the pavement, it is less likely to form thick pavement fissures. However, as a result of climate change, arid areas will increase, causing the previously uncracked low plasticity clays to form desiccation fissures. The earthworks' water balance can tumble due to prolonged drought experienced in the past decades and they can desiccate beyond repair.

Abbreviations

BME Budapest University of Technology and Economics
ClL Low plasticity clay
ClM Medium plasticity clay
ClH High plasticity clay
ClV Very high plasticity clay
HDI Hungarian drought index
OVF General directorate of water management
PDSI Palmer drought severity index
PAI Pálfai aridity index
SPI Standardised precipitation index
SiL Low plasticity silt
SiM Medium plasticity silt
SiH High plasticity silt
SiV Very high plasticity silt

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Author contributions

The first author collected and analysed the data and wrote the manuscript. The second author provided some of the data analysed in the article and read, edited and approved the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets used and evaluated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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