Deterioration of flood protection dikes due to shrinkage cracking

Pathologie des digues à cause de fissures de retrait

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ABSTRACT: An exceptionally long spell of drought in the Tisza valley, Hungary, has led to massive cracking due to shrinkage on several hundred kilometres of flood protection dikes built of rich swelling clay. An extensive research program was launched aimed at revealing the mechanism of cracking and finding effective remedial measures. Regional meteorological data and geological and soil survey data were conflicted with the occurrence and frequency of damage cases. Various geophysical methods were put on field trial in order to find the most suitable non-destructive method for the detection of cracks. Experimental evidence was found to confirm the general validity of a unique linear relationship between loss in moisture content and ensuing volume change, applicable also to the range of partially saturated soils. The mechanism of cracking and its effect on the serviceability of dikes was studied and concepts for remedial measures suggested. The paper reports on various trial rehabilitation works including drainage, upstream lining and diaphragm walls made of self-healing bentonite-based material.

RESUME: Après une très longue période de sécheresse nombreuses fissures de retrait se sont developpées digues construites en argiles venant du lit de la rivière Tisza. Reserches poussées, y compris des études meteorologiques, géologiques, géophisiques et géotechniques ont été effectuées pour trouver les causes et le mecanisme de fissures. Les essais de laboratoires ont approuvées que la relation linéaire connues entre le teneur d'eau et la variation de volume sont valables également pour les sols partiellement saturés. L'article traite l'influence des fissurations sur la stabilité de la digue ainsi que les differents méthodes de la rehabilitation.

1. Introduction

Extreme climatic conditions coupled with other circumstances inherent in the fill material and the mode of construction have led to severe deterioration of old flood control dikes along the river Tisza and its tributaries that drain the Great Hungarian Plain (Figure 1). The extent of the problem is so large and the damage so serious that over certain areas the flood defence situation has by now become critical. These dikes some built a hundred years ago and made of rich swelling clay have experienced intensive cracking over the times. Cracks and cleavages over 10 cm in width and penetrating to several meters are quite common. Investigations and site explorations of heavily fissured dike sections showed that the main cause of cracking was an almost permanent draught which inflicted this region of Europe during the last 10 to 12 years. It appears that in this case normal alternating dry and wet periods and consequent periodical variation of swelling and shrinkage gave way during long draughts to a tendency for monotonous and irreversible drying out that can eventually be blamed for the problems. As a "result", the dikes at places have completely disintegrated by fissuring into a discontinuous heap of blocks and columns.

In general, formation of cracks may be brought about by various mechanical factors (uneven settlements, slide and creep in the slopes, earthquake etc.) as well as by physical processes inside the dam body (drying, swelling) or by a coincidence of both. This paper primarily addresses the problem of volume changes due to desiccation of partially saturated swelling clays. Notes on assessment of the stability and serviceability of damaged dikes as well as on remedial measures will also be given.

2. Factors contributing to the cracking of dikes

History

The construction of the dike system in the Tisza valley started in the middle of the 19th century alongside with the implementation of very ambitious drainage and river training works that resulted in the reclamation of a land of some 15000 sq. kms that had formerly been inundated by annually recurring floods. The embankments have since been gradually developed, enlarged and raised in order to make them more safe and to cope with ever increasing max. flood levels. Reinforcement works were often carried out in emergency situations and all that resulted in typically non-homogeneous cross-sections with shells and capping arranged in a rather haphazard manner (Figure 2). A typical "upgraded" dike from the 1990's should have a cross-section with crest width ranging from 4 to 5 meters, a height of 3 to 6 meters, an average slope of 1 in 3 on the river side and 1 in 2.5 on the protected side.

A glance at the geological map of the Great Hungarian Plain makes it clear that the near surface soils abundant in this region mainly consist of rich swelling clays. So our ancestors had no choice but to build the dikes of such soils not reckoning – at that time – with all the consequences to come.

Soils

The majority of dikes were built of cohesive soils (I_p>20) as shown in the Casagrande chart in Figure 3. Observed shrinkage cracking was invariably associated with the occurrence of highly plastic clays (I_p=50 to 70), with high montmorillonite content as e.g. at the two locations Tarnaméra and Kisköre, selected for further detailed studies. Occasional organic content of up to 5 to 8 percent may also have had a minor role in the formation of cracks. Most of the soils were found to be non-dispersive.

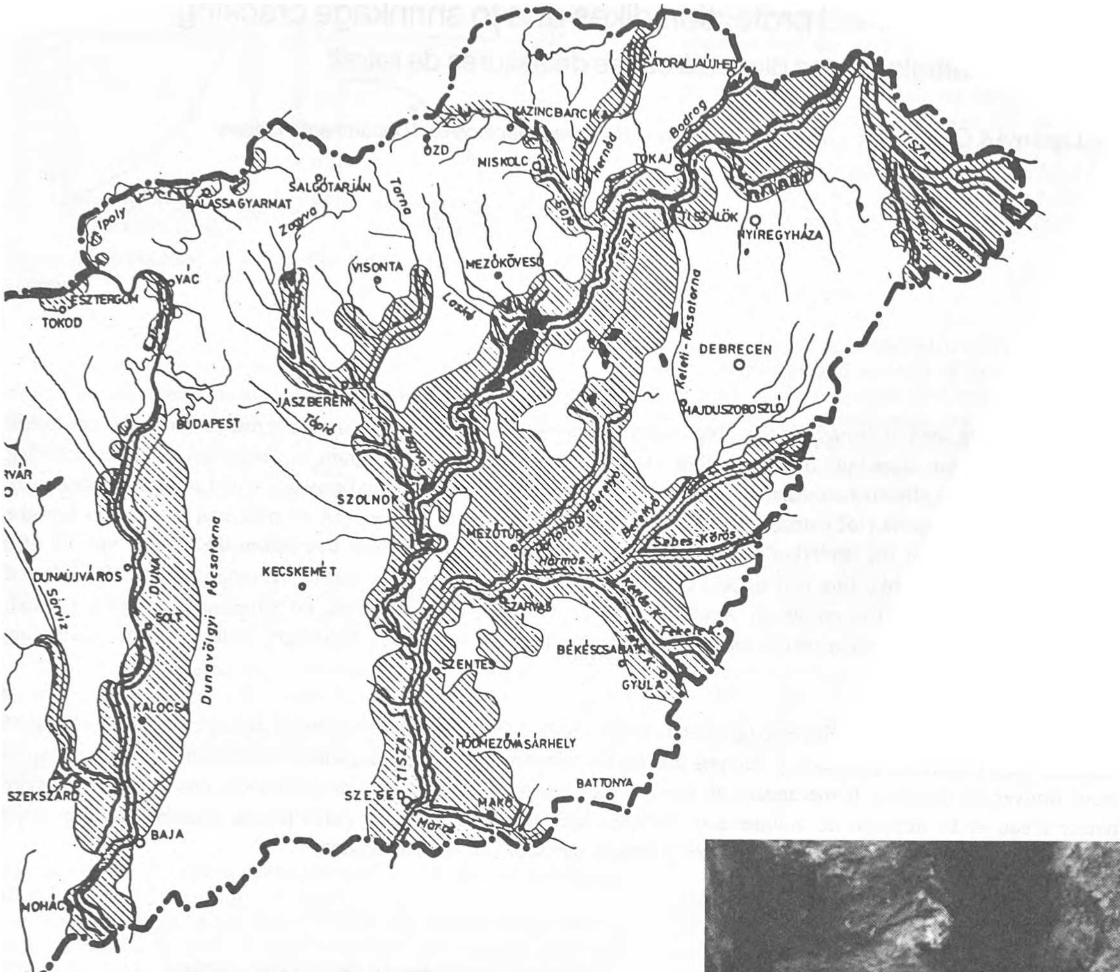


Figure 1.

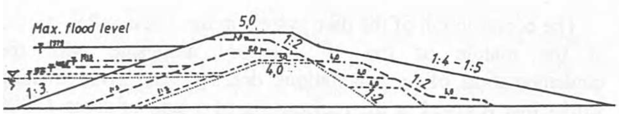


Figure 2.

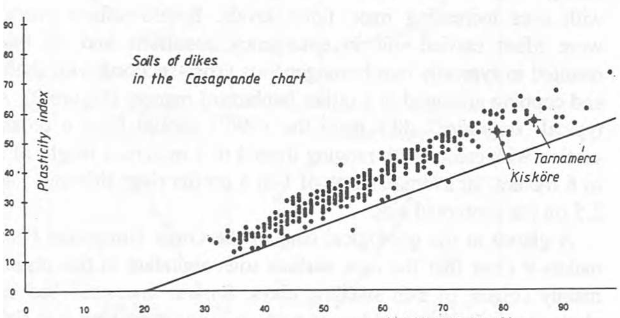
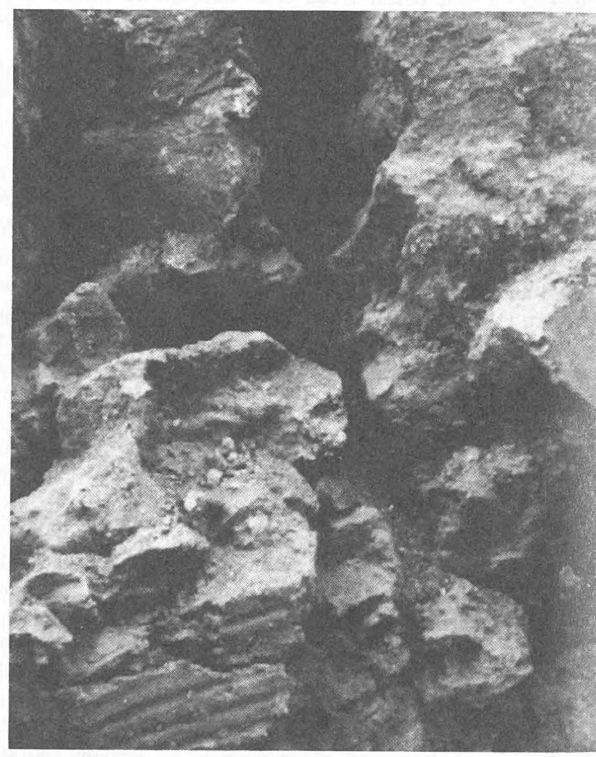


Figure 3



Climate

Hungary has a temperate climate with a yearly precipitation fluctuating between 550 an 700 mm. However, in the last 15 years or so the country has experienced a sequence of extremely long spells of drought with the period of 1989 to 1993 being the driest one in the century. It was the deficit in winter precipitation (Figure 4) that had the worst impact on the ground water and led to a complete upset of the moisture balance in exposed earthworks like dikes.

Impact on dikes

In addition to long periods of extreme droughts no long lasting high floods occurred in the last 20 years. So neither precipitation, nor floods, nor recharge from the ground water have made up the losses of moisture. All these circumstances have led to a monotonous drying out and eventual cracking of the dikes. The attached photo gives an idea of the character of the damage and the size of the cracks, longitudinal ones some times gaping as wide as 5 to 10 cm and penetrating 3 to 4 meters

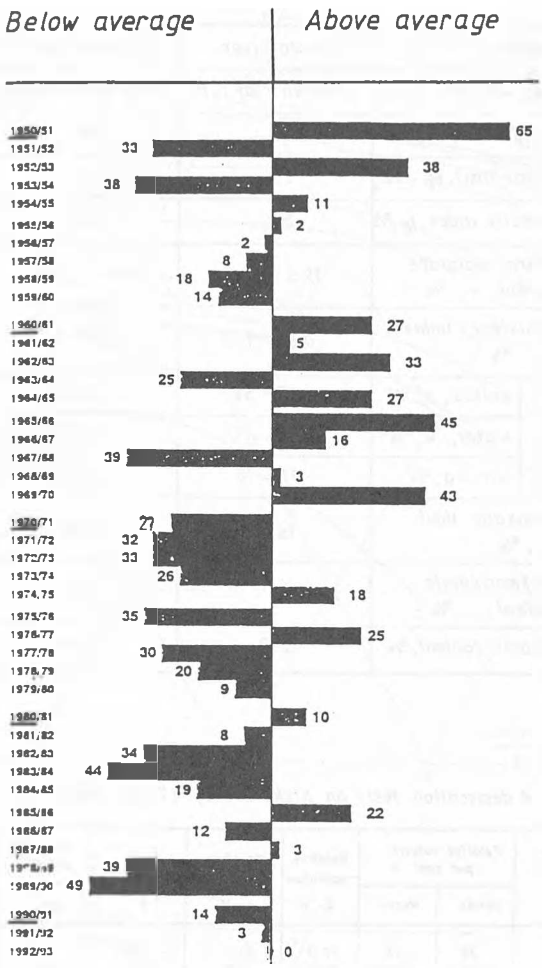


Figure 4. Variation of winte precipitatio (October to March) in Hungary. Figures indicate per cent deviation from average

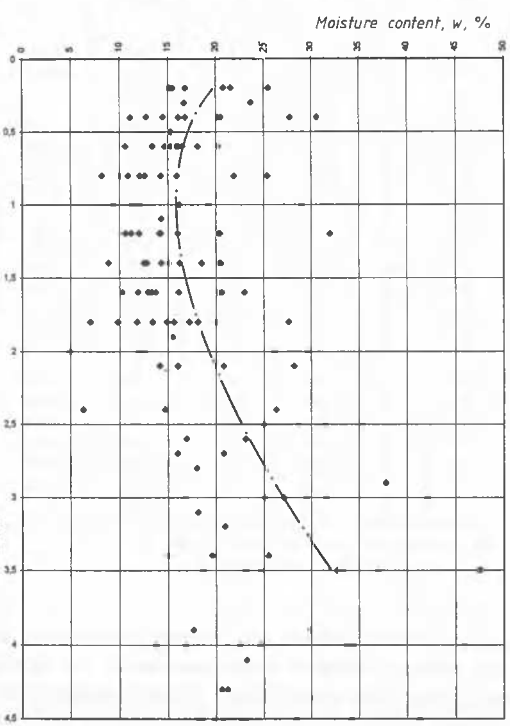


Figure 5.

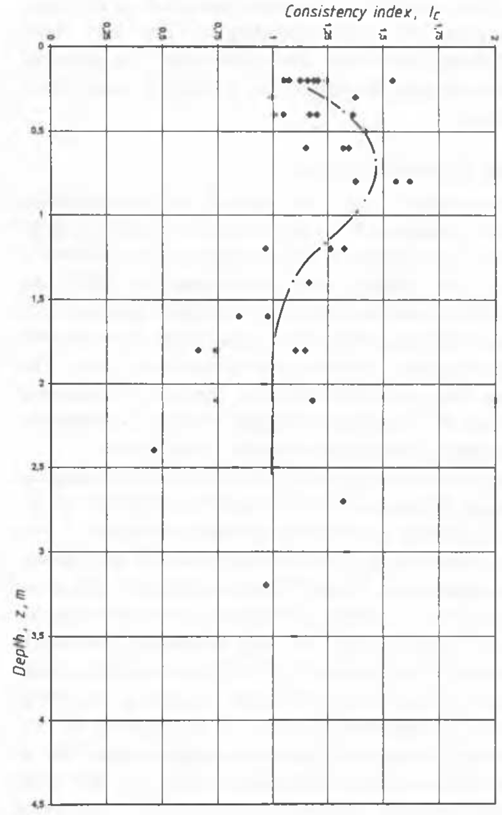


Figure 6.

being the more pronounced. Transverse cracks, not so wide, are also common causing a complete disintegration of the upper part of the dike into a discontinuous mass of blocks and columns. Figure 5 and Figure 6 show the variation of moisture content and of consistency index, respectively, with depth in a typical cracked dam profile.

During occasional short periods of flood only the surface of a dry soil block is moistened, its inner part remains dry. Wounds do not heal as is proved by growing moss on the faces of old cracks and the presence of debris filling the cracks.

Cracks are not readily detected by visual inspection since they are often trampled or grown over by vegetation on the surface while some cracks start from beneath the surface. Conventional auger drilling is not much of help. Attempts were made to use non-destructive geophysical electric resistance method. While this method proved to be successful in identifying critical zones with a likelihood of extensive cracking, it failed to detect the exact location of cracks.

3. Laboratory study of volume changes due to desiccation

Special laboratory tests were carried out with the purpose of obtaining empirical information on the relationships that appeared to control the process of volume change due to desiccation leading eventually to cracking. These were

(i) the relationship between volume change and reduction in moisture content for partially saturated compacted clay, and

(ii) the tensile strength of partially saturated clay.

Two typical clays were selected for detailed testing: one from the Tisza valley (location Kiskőre) and one from the Tarna river (location Tarnaméra). Dikes of other rivers such as Körös and Zagyva were also investigated in a similar manner.

The main physical characteristics of the Tisza and Tarna clays are summarised in Table 1. Note that both clays are of high plasticity and have a high montmorillonite content.

For both clays, the moisture contents measured in the dikes vary between wide limits (corresponding to "dry" and "wet" ambient conditions), and these limits determine the potential range of volume change (shrinkage) that is likely to occur under natural conditions.

Volume change vs. moisture content

Extensive laboratory tests were carried out on cylindrical samples (height = diameter = 6 cm) remoulded at various initial densities and moisture contents. The specimens were allowed to air-dry freely at an average room temperature of 20°C, and weighed and their dimensions measured at regular intervals until no loss in mass was registered. (This "final" state corresponded to a retention moisture content of w=5 to 6 per cent.) The specimens were then oven-dried and their "minimum" dimensions taken. Note that the "minimum" volume was not constant but was markedly dependent on the initial state of the sample.

The process of desiccation can be best followed in a triangular diagram showing the changes in the "phase composition" of the sample. Results with the Kisköre clay are shown in Figure 7. The sides and base, respectively, of the triangle represent the "relative volume" of the component "phases": solids, s, water, v and air, a. (Note that s% +v%+a%=100%). Desiccation curves for samples with the same initial density (s) but increasing volumetric moisture contents (v) e.g. curves N° 1 to 4 show a similar trend: they run "parallel". (On Curve 1, the times elapsed, in hrs, during desiccation are also indicated). Curves 1 to 4 eventually all land at the s side of the triangle (i.e. at v=0 moisture content) but at different final densities (s_{max}) which latter depend on the initial state. The same statement applies to all curves. (The underlying measurements are summarised in Table 2.)

The results for the Kisköre clay are re-plotted in a more familiar form in Figure 8 which shows the relationship between void ratio and moisture content.

The important conclusion that can be drawn from the set of desiccation tests shown in Figure 8 is that the volume change diagrams (i.e. void ratio vs. moisture content lines) for partially saturated samples were invariably parallel to the "theoretical" line which latter assumes the prevalence of complete saturation (S_r=1) throughout the process of desiccation. This finding has led to the construction of a normalised graph (Figure 9) which suggests that irrespective of the fact whether the sample be completely or partially saturated the volume change behaviour due to desiccation is governed by a unique linear relationship

$$\frac{\Delta V}{V_s} = \Delta e = \frac{\rho_s}{\rho_w}\left(w_i - w_r\right)$$

for the range of moisture content

$$w \geq w_{sl}$$

In the formula,

- ΔV: reduction in volume,
- V_s: volume of solids,
- Δe: reduction in void ratio,
- ρ_s: density of solids,
- ρ_w: density of water,
- w_i: initial natural moisture content,
- w_r: reduced moisture content,
- w_{sl}: limit of linear shrinkage.

Note that the shrinkage limit w_{sl} is not easily defined. For convenience it can be taken as the moisture content at which the e vs. w relationship deflects from linearity.

Tensile strength

Preliminary tests on briquette specimens suggest a relationship between the tensile strength and the phase composition (i.e. relative volumes of solids, moisture and air) of the soil (see the triangular chart in Figure 10). For convenience, the results are re-plotted in Figure 11 in a more familiar form as relationship between tensile strength and per cent volume of solids (i.e. dry density), for different values of relative saturation. All samples irrespective of their state of consistency showed typically brittle failure in tension. Further research is needed to clarify the tensile strength behaviour of compacted clay.

Table 1.

Location		Tisza river	Tarna river
Type of soil		Brown clay (CH)	Dark brown clay (CH)
Liquid limit, w_L, %		79	85
Plastic limit, w_p, %		26	27
Plasticity index, I_p, %		53	58
Natural moisture content, w, %		19.3 - 30.2	19.4 - 25.5
Consistency index, I_c, %		0.92 - 1.12	1.03 - 1.13
Relative volumes	solids, s, %	48 - 54	47 - 52
	water, w, %	30 - 41	29 - 34
	air, a, %	11 - 16	19
Shrinkage limit, w_s, %		16.7	14.9
Montmorillonite content, %		56	80
Organic content, %		2.2	3.28

Table 2.

Data of desiccation tests on Kisköre clay (Tisza valley)

Symbol of test	Relative volume per cent *		Relative saturation	Moisture content	Void ratio	Relative volume change
	Solids	Water	S_r, %	w, %	e	Δe
1	38	56	90.3	51.7	1.623	1.161
	44	50	89.3	39.9	1.273	0.802
	50	43.5	87.0	30.5	1.000	0.529
	53	40	85.1	26.5	0.887	0.416
	60	30	75.0	17.5	0.667	0.196
	64.5	20	56.3	10.9	0.550	0.080
	67	10	30.3	5.2	0.492	0.022
	68	0	0	0	0.471	0
2	40	15	25.0	13.2	1.500	0.227
	42.5	10	17.4	8.3	1.353	0.147
	44	0	0	0	1.273	0
3	40	23.3	38.3	20.4	1.500	0.459
	43	20	35.1	16.3	1.326	0.285
	47	13	24.5	9.7	1.128	0.087
	48	10	19.2	7.3	1.083	0.042
	49	0	0	0	1.041	0
5	37	41	65.1	38.9	1.703	0.883
	40	36	60.0	31.6	1.500	0.682
	44	30	53.6	23.9	1.273	0.455
	50	20	40.0	14.0	1.000	0.182
	54.5	10	21.9	6.4	0.835	0.017
	55	0	0	0	0.818	0
10	49	35	68.6	25.1	1.041	0.454
	52	30	62.5	20.2	0.923	0.336
	56	24	54.6	15.0	0.786	0.198
	58	20	47.6	12.1	0.724	0.137
	60	16	40.0	9.4	0.667	0.079
	62	10	26.3	5.7	0.613	0.026
	63	0	0	0	0.587	0

N.B: * [solids %]+[water %]+[air %] = 100
Density of solids ρ_s = 2.85 g/cm³

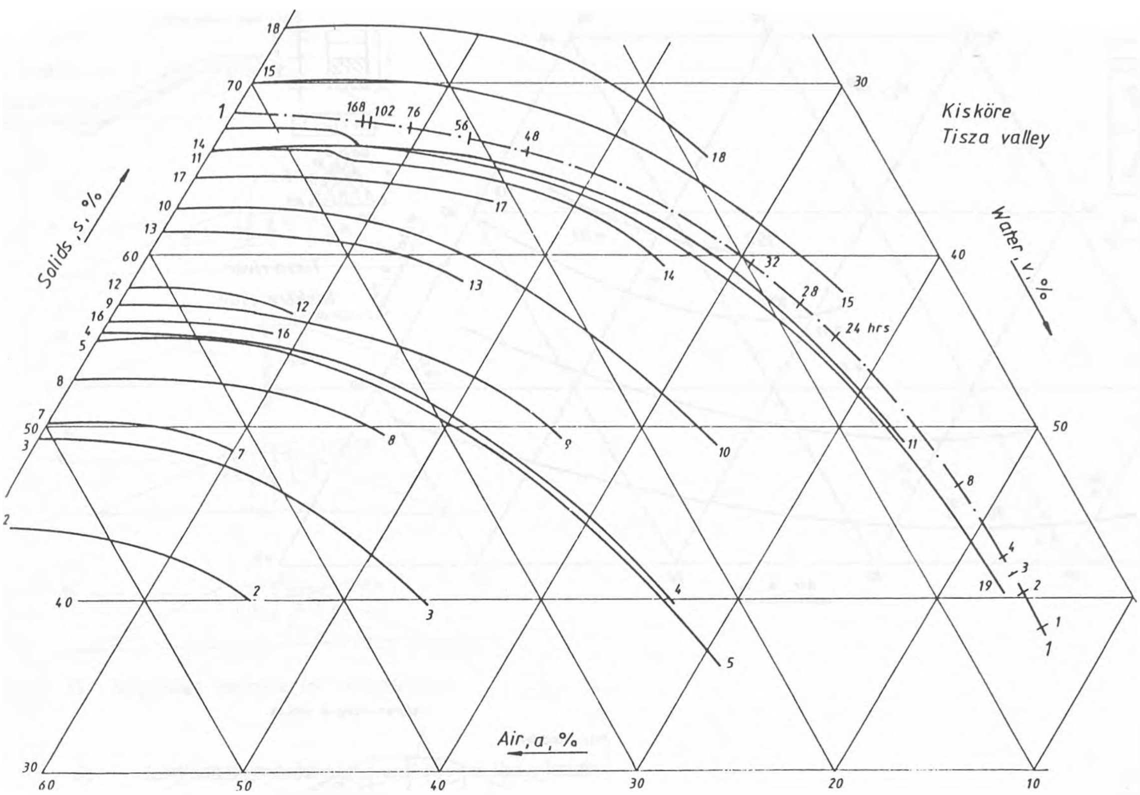


Figure 7.

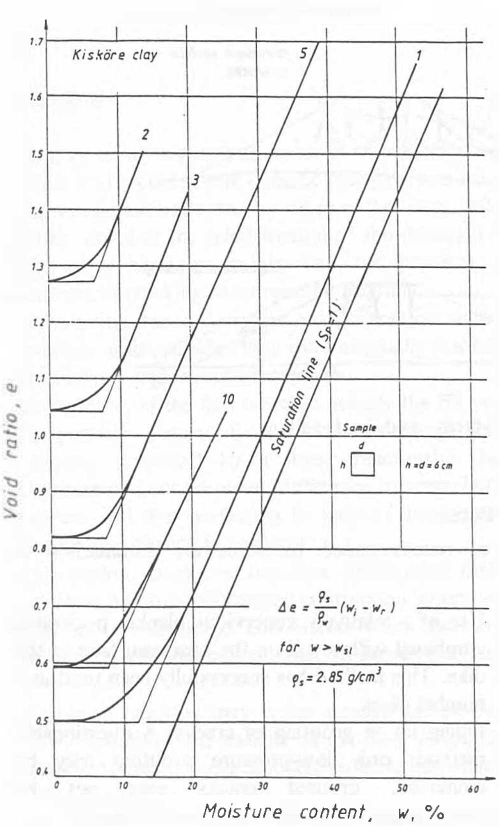


Figure 8.

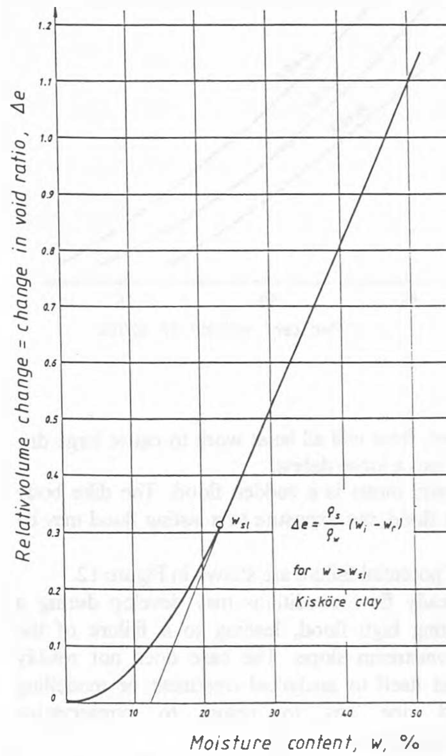


Figure 9.

4. Impact of cracking on serviceability. Remedial measures

The main objectives of the research project cited in the preceding were to assess the stability and serviceability of the damaged dikes and to put forward recommendations for remedial works. In the following, a brief account is given of these considerations.

Stability of the dikes

A cracked dike if left unattended may deteriorate in its state even in relatively dry weather conditions. Continued drying,

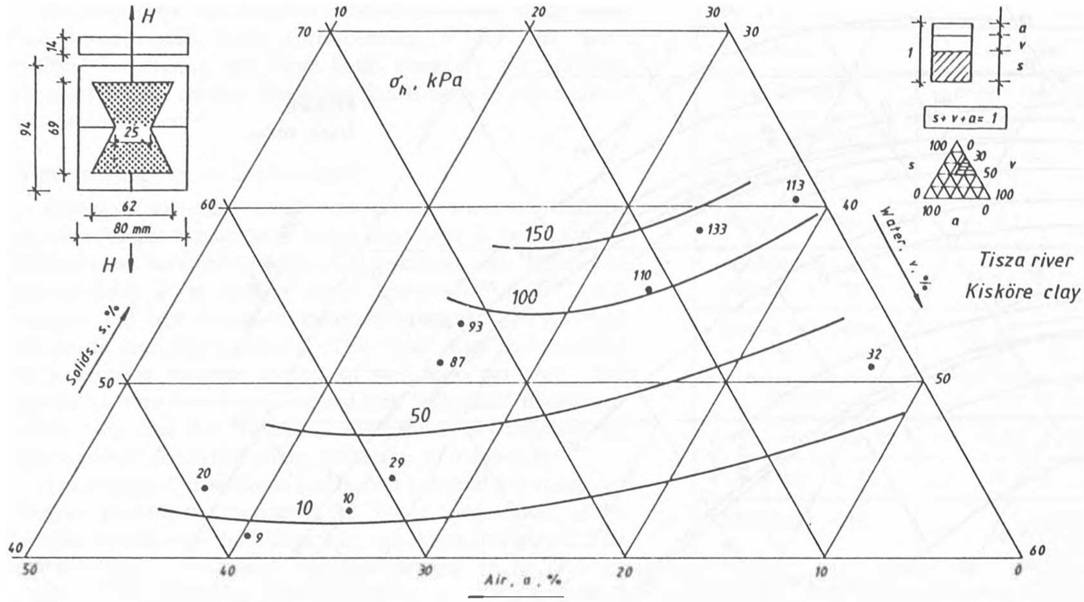


Figure 10.

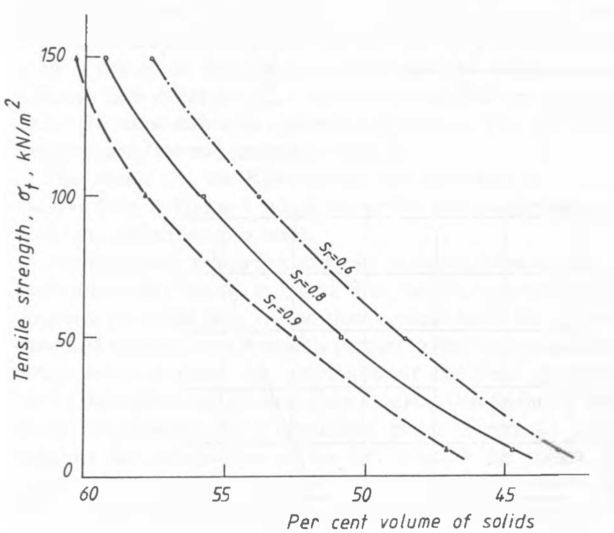


Figure 11.

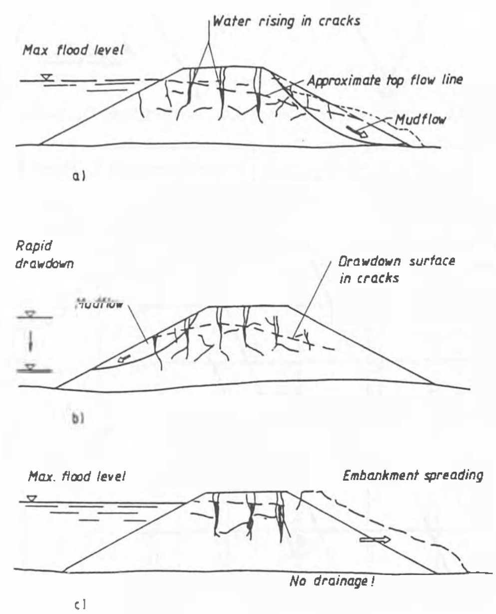


Figure 12. Typical modes of failure

infiltrating rain water, frost will all be at work to cause large dry blocks to fragment into a loose debris.

However, the main threat is a sudden flood. The dike body may survive a short flood, but exposure to a lasting flood may be fatal.

Typical cases of potential failure are shown in Figure 12.

Case A: steady flow conditions may develop during a lasting high flood, leading to a failure of the downstream slope. The case does not readily lend itself to analytical treatment or modelling and one has to resort to conservative assumptions.

Case B: Rapid drawdown leading to failure of the upstream slope. A number of cases of such failure has been reported.

Case C: Hydraulic fracturing, this being the worst case leading to complete dike failure. The fact that wide longitudinal cracks exist which are undrained towards the upstream slope makes this hazard very real.

Remedial measures

A series of recommended measures are summarised in Figure 13.

a) Use of a relatively impervious blanket preferably combined with a foil on the upstream face of the dike. This method has successfully been used in a number cases.

b) Filling up or grouting of cracks. A questionable method: only low-pressure grouting may be employed, grouted cracks may not be interconnected to form an impervious barrier.

c) Cut-off (diaphragm) wall. This seems to be a promising approach. Trials with the use of a patented self-healing stone chipping/bentonite mixture jetted dry into a narrow slot gave satisfactory results.

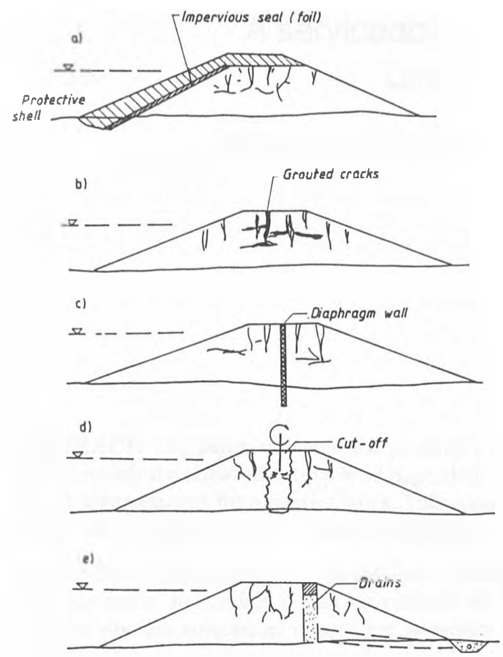


Figure 13. Suggested methods for rehabilitation

d) Jet-grouting: field trials are yet in the planning state.

e) Drains and filters. This is a conventional solution used in small earth dams. The installation of drains into existing dikes does not present insurmountable problems.

Conclusions

Dam material, history and mode of construction coupled with the impact of recent severe climatic changes have led to cracking of unprecedented scale on clay dikes in the Tisza valley. A study primarily aimed at the rehabilitation of the damaged dikes, gave at the same time an insight into the physical causes and mechanism of cracking in compacted clay fills.

- Contraction due to desiccation is likely to occur in all types of cohesive soils provided they were originally placed into the fill at relatively high moisture contents.
- Irrespective of the fact whether initially the fill be completely or partially saturated, the volume change behaviour is uniquely governed by a linear relationship between the moisture content potential (difference between initial moisture content and that pertaining to limit of linear shrinkage) and the ensuing change in void ratio.
- Desiccation produces transient differential distribution of moisture and thus differential contraction strains which in turn may lead to cracking. This occurs when the tensile stresses induced by differential construction exceed the tensile strength of the soil.
- Extensive cracking may create serious and permanent threat to serviceability and stability of the dike. A spontaneous self-healing of cracks upon exposure to fresh inundation cannot be relied upon.
- The hazard of extensive shrinkage cracking can be mitigated by possibly avoiding the use of highly swelling clays and by properly conditioning the soil during construction of the fill, i. e. by placing it at, or just slightly above, the optimum moisture content and compacting to a relatively high (min. 90 per cent) density.