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The paper was published in the proceedings of the 6th International Conference on Geotechnical and Geophysical Site Characterization and was edited by Tamás Huszák, András Mahler and Edina Koch. The conference was originally scheduled to be held in Budapest, Hungary in 2020, but due to the COVID-19 pandemic, it was held online from September 26th to September 29th 2021.

Geotechnics and Soil Sciences: multidisciplinary investigation of a saline lakebed

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ABSTRACT: Investigation of a subject usually means that the tools of some field of study are used in order to obtain information. When similar disciplines, such as geotechnics and soil sciences are evaluating the same object, the diverse ways of collecting information leads to different conclusions. However, they study the same subject, only from distinct points of view. In the case of lake Szappanos, the properties of the subsoil were measured by the equipment of soil sciences and geotechnical engineering, and the results and correlations of the different parameters are collected and evaluated in this paper.

Keywords: geotechnics; soil sciences; dispersive soil; saline soil

1. The nature of dispersive soils

Soils are formed by physical, chemical and biological processes. In result, the soil is a composition of three different phases; the solids, which are the main component of the soil, and the liquid and gaseous phases filling the pores between soil grains or particles.

Clay soils are usually considered as water-tight and erosion-resistant materials, but in some cases, failures appear, especially if they are used as fill material for flood protection structures such as earth dams or embankments (see Fig. 1.).

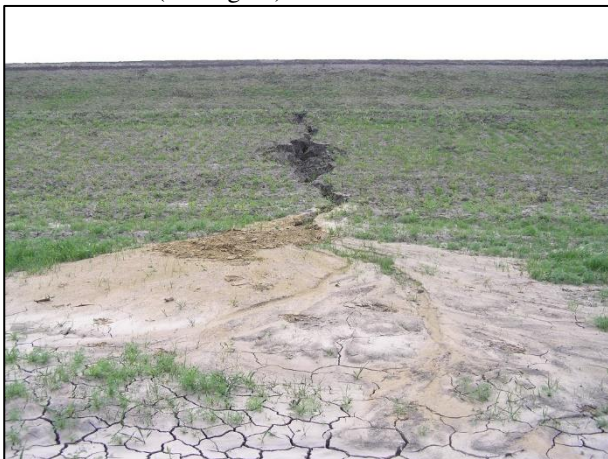


Figure 1. Outwashed material due to dispersive behavior in an embankment

The first experiences with this phenomenon are dated back to the early 1930's, and detailed investigation took place in the 1970's [1]. It is worth to mention that in Hungary, investigations took place only a few years later, Szepessy wrote the articles about soil dispersion in the early 1980's [2].

Despite the numerous ways of investigation, some parts of the behavior are still unclear. The trigger

mechanism of the dispersive behavior is also defined different ways.

Mitchell [3] stated that the effect of the dispersion is the structural breakdown due to the resultant of the repulsive and attractive forces acting in a soil mass (see Fig. 2.). It suggests that the dispersive behavior is depending on the distance from the clay surface and the ionic concentration of the pore water. This assumption leads to the double layer theories that are known for soils.

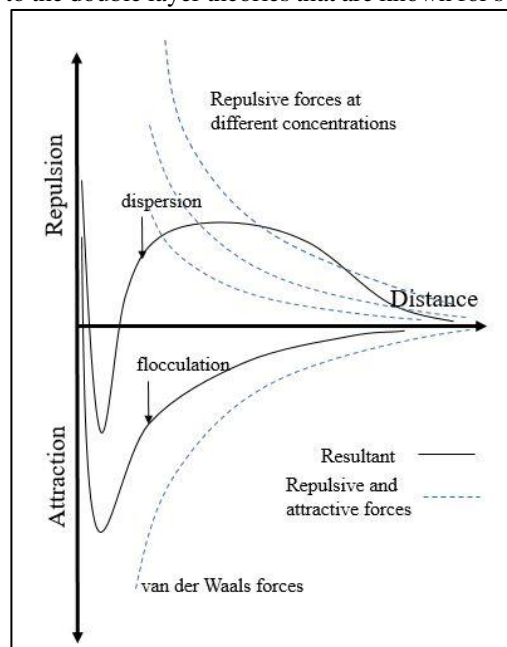


Figure 2. Repulsive and attractive forces acting on the surface of soil colloids (after Mitchell [3])

Based on Filep [4] the Helmholtz, Gouy-Chapman and Stern double layers that defined the distribution of the ions inside the diffuse double layer around the surface of the hydrated soil colloids.

Szabó [5] suggested that the double layer follows an exponential decrease from the surface of the clay platelet by the function of Eq. (1)

$$\Psi_x = \Psi_0 \cdot \exp(-\kappa \cdot x) \quad (1)$$

where Ψ_x is the potential at the distance of x from the surface, Ψ_0 is the electric potential at the surface of the colloid particle, κ is the constant depending on “density” of the double layer.

In Eq. (1) κ defines the parameters affecting the thickness of the double layer explained in Eq. (2)

$$\kappa = \sqrt{\frac{2 \cdot \pi \cdot \eta_0 \cdot \epsilon^2 \cdot v^2}{D \cdot k \cdot T}} \quad (2)$$

where η_0 electrolyte concentration (mol/cm³), ϵ is the unit electronic charge (coulomb), v is the cation valence (-), D is the dielectric constant of the medium (-), k is the Boltzmann constant (J/K), T is the temperature (K).

The theory correlates with Carey’s [6] where he states that the breakdown of soil structure occur when the connections between clay platelets are broken, and this breakdown is dependant of the relative amounts of sodium and calcium ions between the platelets.

Carey [6] suggests, that if there are both sodium and calcium ions between the platelets, when the soil gets wet, the hydrated sodium becomes larger than the hydrated calcium. It also causes expansion which will push the clay platelets farther of what the electrostatic bonds of the calcium ions can bear. This leads to the breaking of the bonds of the calcium ions, and since the sodium is only mono-valent, the it can only connect to one of the surrounding platelets, this phenomenon leads to the separation of the clay particles which is called dispersion (see Fig. 3.).

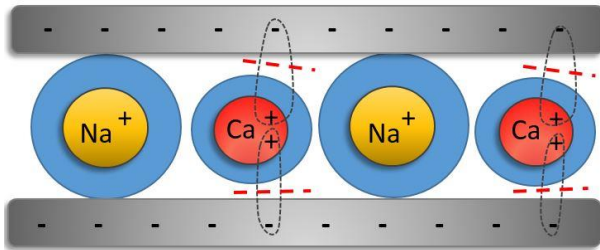


Figure 3. Dispersion due to the hydration of the sodium and calcium ions between two clay platelets (after Carey [6])

The ICOLD bulletin [7] states that dispersion, or deflocculation occurs when the clay gets into interaction with relatively pure water. The water could be a rainfall and the runoff on the surface, but a flood too.

Sherard [8] also connected the behavior to the physico-chemical composition, by the measurement of the amount of exchangeable sodium in the soil mass. He defined categories when plotting the total dissolved salts (TDS) in the sample to the amount of sodium, kalium, calcium and magnesium (see Fig. 4.), and the point of the sample falls into a category called:

- dispersive
- intermediate
- non-dispersive

This method however proved to be a bit simplified, since it needs at least 60 % of the dissolved salts to be sodium to be categorized as dispersive, while in many cases with less sodium content soil dispersion was measured [9].

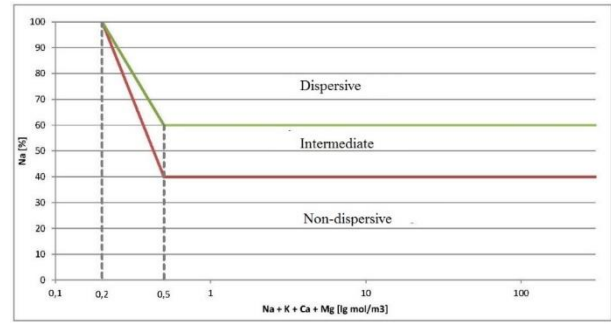


Figure 4. Dispersive categories based on the amount of exchangeable sodium (after Sherard [8])

Based on the DPIW [10] the tunnel erosion, which is the typical failure mechanism of the dispersive soils can occur, when the ESP value is greater than 6.0 %, where ESP is the exchangeable sodium percentage:

$$ESP = \frac{Na}{(Ca+Mg+K+Na)} \cdot 100 \quad (3)$$

It is worth noticing that the denominator in Eq. (3) is the TDS value. In the earlier researches more than 10 % of ESP was considered as dispersive behavior, but based on DPIW the lower value, 6.0 % is enough for further testing, or investigation of the material.

The explanation can be found in the properties of the clay minerals. In slightly saline water, sodic soils swell, but generally do not disperse. The clay platelets remain intact.

The problem with these theories is that they are hardly applicable in the geotechnical practice, since when evaluating a soil deposit for embankment construction chemical test, or equipment to determine the physico-chemical composition is barely used.

Another disadvantage is that the dispersive behavior shows very poor correlation with “regular” soil parameters such as the Atterberg-limits or the coefficient of permeability [11].

1.1. Experiences with dispersive clays

Dispersive clays appear in many parts of the world. They are known in the USA as Badlands.

They mostly weathered from marine sedimentary rocks, however in South Africa (Zimbabwe, Eswatini and South Africa) their formation is connected to igneous rocks, commonly with the erosion of granite and granodiorite or sandstone [7].

They mainly appear in areas where the annual rainfall is less than 850 mm. In some parts of South Africa dispersive soils have to be used for construction purposes since no other soil material was available [12].

In Europe they are common in Italy [13, 14] and they are present in Hungary in an area called Tisza-valley.

Dispersive clays are known for their distinct erosion. These forms were monitored in Italy for more than 20 years [14].

Dispersive clays are usually first identified after heavy rains as they are easily eroded. The mechanism of dispersivity is reasonably well understood. An effort has been made to use Atterberg’s limits, shrinkage limit and unconfined compressive strength to quantify the dispersivity of a soil [15].

Several study worked with dispersive soils, in some cases native and artificial soils mixed with different chemicals, were used for the study [16]. To better understand the erosion processes related to dispersive soils (badland formations) some researchers only relied on mineralogical and geochemical test [17].

2. Soil sodicity, soil salinity

Saline soil is an agricultural term, referring to a soil which went under the process of increasing the salt content known as salinization.

Salinization can be caused by natural processes such as mineral weathering or by the gradual withdrawal of an ocean. It can also come about through artificial processes such as irrigation.

Sodicity is the presence of a sufficient amount of sodium ions on the cation exchange surfaces of clay platelets to cause soil dispersion [6]. Soils may be both sodic and saline.

The saline content and the surface of sodic soils are leading to an assumption that there might be a relationship between the term sodic soil and dispersive soil. She et al. [18] suggests, that the increasing of the sodicity of soils or decreasing the salinity of the soil solution increases the repulsion forces between clay particles.

Pratt and Suarez [19] showed, that the sodicity and salinity values can result the dispersion or swelling of the clay soil. This enhances the process of aggregate breakdown, and if it is combined with heavy runoff, it increases the erodibility of sodic soils.

The chief characteristic of sodic soils from the agricultural stand point is that they contain sufficient exchangeable sodium to adversely affect the growth of most crop plants. For the purpose of definition, sodic soils are those which have an exchangeable sodium percentage (ESP) of more than 15 %.

Excess exchangeable sodium has an adverse effect on the physical and nutritional properties of the soil, with consequent reduction in crop growth, significantly or entirely.

The soils lack appreciable quantities of neutral soluble salts but contain measurable to appreciable quantities of salts capable of alkaline hydrolysis, e.g. sodium carbonate.

The electrical conductivity (EC) of saturation soil extracts are, therefore, likely to be variable but are often less than 4 dS/m (at 25 °C).

The pH of saturated soil pastes is 8.2 or more and in extreme cases may be above 10.5. For sodic soils with pH higher than 8.0 there is a good estimation for the ESP value based on the pH of the saturated soil paste (see Table 1.).

Table 1. Approximate ESP values based on the pH of the saturated soil paste [20]

pH of saturated soil paste [-]	Approximate ESP [%]
8.0-8.2	5-15
8.2-8.4	15-30
8.4-8.6	30-50
8.6-8.8	50-70
8.8-	70

Based on Table 1. pH 8.2 can be referring to a soil which has an approximate ESP value of 15 %, what is enough to be called dispersive hence DPIW suggests that ESP higher than 6.0 % is enough to be susceptible of dispersion. This suggests that the dispersive behavior is a weaker criteria than the sodic at this standpoint.

3. The site: Lake Szappanos

In cooperation with members of the Institute of Soil Sciences and Agricultural Chemistry (MTA-TAKI), we had an opportunity to investigate materials taken from an area called Lake Szappanos, which area proved to be a saline lakebed.

The site lies in the southeastern part of Hungary, near Bócsa. The lake was formed on the middle of the Danube-Tisza ridge, on a former Danube alluvial fan. During its Quaternary evolution, following the cessation of the alluvial deposition, eolic sedimentation, mostly loess and re-deposited Danube-sediment as blown sand became decisive [21].

During the Holocene, a pond formed in the area, which became more permanent due to rainfall characteristics, and the former carbonate mud formation was replaced by peat formation. In the lakebed Pleistocene and Holocene sediments as loess and windblown sand built up the young geological formation of the area, with interbedded clay, mud and organic matter-rich lenses and coarse alluvial sediments in depth. The 20-80 cm thick carbonate mud is considered the characteristic sediment of the lakebed [21]. The geological map of the site is shown at Fig. 5.



Figure 5. Map of the site. The yellow areas representing the wind-blown sand, while the blue ($1Qh_2^{mi}$) area is the mud/silt formation

4. Equipment used

4.1. Testing of dispersive behavior

Several methods are available for testing. Field testing, like the crumb test, or the drop test can give a quick, but not so precise guide in the evaluation of dispersive clays, however, the first step of the identification is to locate the dangerous sections of the dikes. These simple field testing methods are capable to give a rough estimation of the suspected dispersive behavior of the soils, based on them samples can be collected for more accurate laboratory testing.

The most recognized laboratory tests is the pinhole test. The method and the device was developed by Sherard et al. [22]. The device and the method is based on a hydraulic approach.

For the test a compacted (mostly with a Proctor device) cylindrical specimen is needed. The method simulates the flow of water through a crack by punching a 1.0 mm diameter hole in the specimen with an iron pin, and distilled water can percolate through it. If the sample is a dispersive clay, the flow breaks down grains from the soil structure, and the flowing water becomes a dispersive solution.

The equipment is capable of modelling different hydraulic conditions, therefore 4 different pressure heads can be applied, 50, 180, 380 and 1020 mm. Dispersive clays erode at the smaller heads, consequently erosion-resistant soils can withstand 1020 mm water pressure without major particle movements. During the test, the flow velocity, and the eroded grains are observed. The device can be seen in Fig. 6.

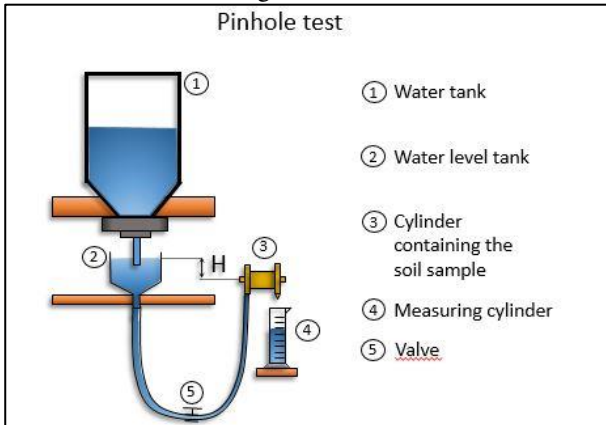


Figure 6. Pinhole test device based on Sherard et al. [22]

One of the test should be highlighted is the determination of the Galli-type void ratio. The Gall type void ratio (e_k) shows the sensitivity of cohesive soils to water.

The test is based on the sedimentation of soils in a test tube under 48 hours. At the end the measured volume of the soil sediment is the basis of the calculation by Eq. (4).

$$e_k = \rho_s \cdot \frac{V}{m_d} - 1 \quad (4)$$

where ρ_s is the bulk density of the soil (g/cm^3), V is the volume of the sample (cm^3) and m_d is the measured dry mass of the soil sample (g).

After the 48 hours sedimentation if the soil contains large amount of fine grains, some fine particles are not able to settle due to the resultant of the forces acting. For small particles the resultant of the uplift of the water and the self-weight can lead to a state where the particle is at a floating state and cannot settle in time.

Based on the Galli [23] the method distinguishes the soils by their swelling characteristics and classifies the samples into four categories shown in Table 2.

Table 2. Galli-type void ratio evaluation

Evaluation	Galli-type void ratio (e_k)
Aggregating	$0.0 < e_k \leq 2.0$
Watertight	$2.0 < e_k \leq 3.5$
Loosening	$3.5 < e_k \leq 6$
Diffluent	$6 < e_k$ or "V" cannot be measured

The outcome of the test distinguishes the two main result, in one case an exact volume can be measured, and the Galli-type void ratio can be calculated. While in the other case there is no significant border of the settled soil particles and the water on top of them, but there is a turbid mixture of solids and water (see Fig. 7.).

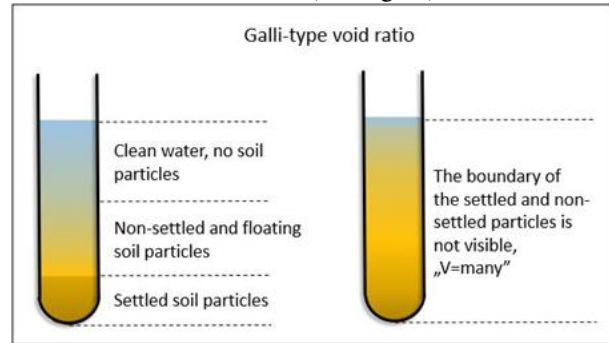


Figure 7. Outcomes of the Galli-type void ratio test

4.2. Testing of sodic behavior

Based on Waskom et al. [24] the main causes of saline soils are measurable by electrical conductivity (EC), pH, and high sodium content. Therefore the laboratory testing is based on the measurement of these three. All testing was performed on a soil suspension prepared by the following order:

- Soil samples are dried in 105°C in a heating oven.
- 30 grams of the soil are weighted out with grain size less than 2 mm-s.
- The dry soil is mixed with 75 cm^3 of boiled distilled water to create a 1:2.5 proportion suspension.
- The soil suspension is at rest for 24 hours.

After the 24 hours three testing method can be performed in the following order:

- measurement of electrical conductivity,
- measurement of pH,
- measurement of pNa.

Different order of measurement can lead to misleading results, because during the measurement of pH ions can get to the solution, which leads different value of the EC, therefore the electrical conductivity testing has to be the first to perform.

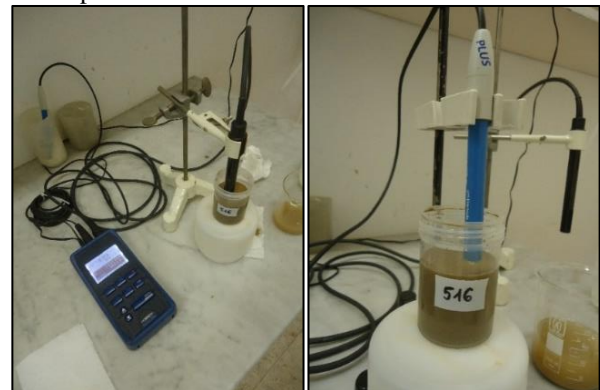


Figure 8. EC measuring equipment (left), and different measurement head for the pH value (right)

Before the measurement takes place the suspension has to be shaken to prevent any sedimentation which can stick to the measuring head, and giving an inaccurate

result. Fig. 8. shows the equipment with the measuring unit. The measurement of the pH value is performed with the same equipment but different head.

4.3. Geophysical testing

Since the nature of the dispersive behavior is strongly connected to its physico-chemical composition, geophysical processes which are defined by measuring electrical properties of soil layers are applicable to investigate the properties of dispersive soils.

The section of geophysics which aims to image the subsurface by using the electric potential of the materials are the electric resistivity methods. The idea behind it is related to Ohm's law measuring the resistance, where resistance is defined by the used voltage divided by the current, and the value of the material's resistance is dependant on the resistivity of that material.

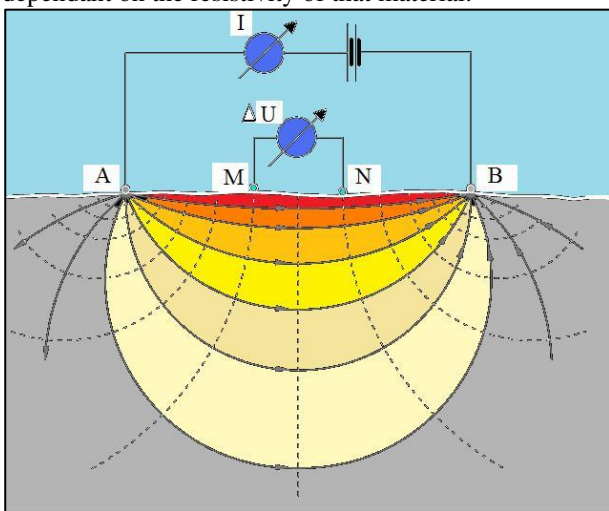


Figure 9. Wenner array

The measurements are using a resistivity meter and four electrodes, two of them are current electrodes (A and B), while the other two are potential electrodes (M and N). The resistivity meter usually acts as a voltmeter (measuring V), and current meter (measuring I).

There are several arrays of these four electrodes depending on the site, the depth and the area of the subsol which is under investigation.

For flood protection structures such as dikes or earth dams, the Wenner array is the best array applicable. In this case the two outer electrodes (A and B) and the two inner electrodes are (M and N).

The resistivity of the subsurface layers can be found by increasing the distance between the electrodes while maintaining the location of the center point of the array. Detection of horizontal changes of resistivity is achieved by moving the four electrodes across the surface while maintaining constant electrode separation. The resistance can be calculated: .

$$\rho_a = 2 \cdot K \cdot \frac{\Delta V}{I} \quad (5)$$

where K is a correction factor which can be calculated by the setup distances of the array so two measurement will be comparable. The setup of the method and the layout of the electrodes can be seen on Fig. 9.

The method is applicable in the case of dispersive soils, when using it on a dam crest, the longitudinal profile can be seen by the measured resistivity. This way the zones inside the dam, where dispersive soils are present are visibly distinguishable from other soils since they represented by zones of relatively low resistance values.

An example for the application is shown at Fig. 10., where a 400 m long embankment section along river Zagyva shows low resistance zones [25]. Due to the cations present among the clay particles in case of dispersive clays these types of soils are considered as good conductors. Field measurements show that in case of wet ground or even moderately dry conditions, this statement is true. As a result of the good electric conductivity, it is not rare to have as low resistivity values as $1 \Omega \cdot m$. In Fig. 10. The most dangerous places regarding tunneling erosion are the white low resistivity areas. Additionally, samples were taken from the embankment to verify the method. Blue dots are marking the spots of non-dispersive samples (ND1 and ND2), while white dots are marking the sampling place for dispersive categories (D1 and D2). The half blue half white markers indicate the interim samples (ND3 and ND4).

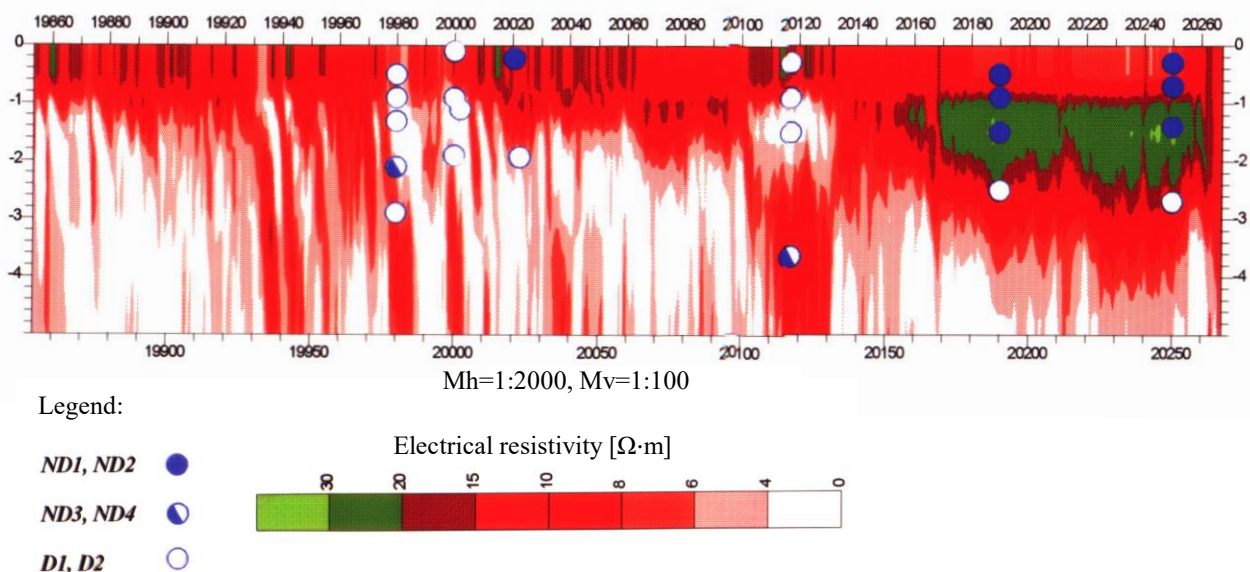


Figure 10. Identification of dispersive soils with in-situ method [25]

It is worth mentioning that there is a laboratory testing way of the electrical resistivity. KBFI-Triász Kft. has built a laboratory testing equipment where based on the idea of the field electric resistivity measurement, the samples can be measured between laboratory circumstances in a sample box to which electrodes can be attached by the setup of the electric resistivity measurement setups.

This was a compacted sample can be examined by different measurement arrays. The sample box and the measurement unit are shown at Fig. 11.



Figure 11. Laboratory measurement equipment for electrical measurement [26]

The laboratory device has advantages and disadvantages, since it provides quick and easy measurement, the back side of it is that the result is highly depending on the water content of the sample, which can be vary from what is present on the site.

The compaction of the sample needs to be close to what can be measured in the embankment to get a good correlation between the behavior of the sample and the structure.

5. Test results

During our research, the Institute of Soil Sciences and Agricultural Chemistry provided us soil samples from the area Lake Szappanos, on which earlier experiments were carried out.

Earlier test from the workers of the Institute for Soil Sciences and Agricultural Chemistry [21] showed that the site of Lake Szappanos was desiccated in 2015.

The ionic composition of the lakebed was dominated by Ca^{2+} , Mg^{+} and HCO_3^{-} ions, while the surface water chemistry showed that the accumulated water in the lakebed shall originate mostly from rain.

The earlier test results on the samples from the site are collected in Table 3.

Table 3. Previous test results

depth [m]	2014 autumn		2015 summer		average	
	pH	EC	pH	EC	pH	EC
	H ₂ O	μS/cm	H ₂ O	μS/cm	H ₂ O	μS/cm
1,0-1,1	10,17	533	10,12	477	10,1	505
1,1-1,2	10,05	523	10,11	499	10,1	511

To be able to compare the results, geotechnical tests were carried out on the samples. During the investigation, only a small amount of sample was available after the testing of the soil chemistry parameters, therefore it needed careful planning of which geotechnical tests should be done.

For our purpose Galli-type void ratio and pinhole tests were carried out. The samples are shown at Fig. 12.



Figure 12. Samples from Lake Szappanos

During the Galli-type void ratio tests, the soil mixture showed very poor sedimentation, and after 48 hours there was barely any settled soil grain, but the mixture was rather turbid.

The sample was classified as diffluent since the volume of the settled soil grains could not be measured on both samples.

The pinhole test was prepared as described in chapter 4.1. Both samples showed great flow velocity and visibly dark water during the experiment, at the smallest difference in pressure head between the two sides of the sample (5 cm), where the test was ended too [27].

At the small head value and the large amount of water seeping through the sample, the test concluded in D1 dispersive category for both soil samples, and for the repetitions. The results are collected in Table 4.

Table 4. Geotechnical test of sodic soil

depth [m]	Dispersive category		Galli-type void ratio	
	1,0-1,1	D1	D1	Diffluent
1,1-1,2	D1	D1	Diffluent	Diffluent

Earlier researches [6, 9] stated that the dispersive behavior is connected to the excess amount of sodium in the soil structure. shows the results of pNa measurement, which is identical to the pH, the negative logarithm of the sodium ion concentration in the soil suspension.

Test were carried out on soils which were proven to be dispersive based on the pinhole test. Dispersive soils pNa values were measured of 1.97-3.22, while in the case of intermediate soils pNa 1.82-3.53 was observed.

The EC measurement showed the similar tendency, the wider range of values, but no significant differences between the two groups. This led to the assumption that although dispersive behavior cannot be independent from the presence of sodium ions, there needs to be some other characteristic of the soil, which causes the unfavorable property.

At the end it can be stated that the parameters of soil dispersibility are in many cases still hard to grasp, and when large amount of samples needs to be evaluated, a laboratory testing program should be installed, which allows engineers to rule out samples probability for soil dispersion, by using “simpler” tests as filter criteria in order to reduce the amount of laboratory testing requirements [28].

6. Conclusions

In geotechnical engineering, clays are considered as watertight and erosion-resistant materials, therefore they

are used in dikes and earth dams as a fill material to prevent seepage, and leakage problems on the downstream face.

In some cases these cohesive soils behave in the presence of water like there were little bonding between the clay platelets, and the flow of the water can be enough force to break down the soil structure and begin to erode the dike. These unusual soils are referred as dispersive soils, and their biggest disadvantage is the likelihood of erosion due to rainfall or surface runoff.

This nature of the dispersive (clay) soils are leading to the necessity to monitor and evaluate dikes in order to prevent the failures due to the unfavorable properties of the soil.

Earlier experiences and studies showed, that source of the behavior can be found in the examination of the physical and chemical properties. Therefore several laboratory testing method were developed (ESP, SAR, EC, pH measurements, etc.) to get a better point of view on the properties of dispersive soils.

This idea correlates with the idea of Mitchell [3] which states the importance of the clay minerals in the soil structure. Test results showed that in many cases the dissolved salts and ionic composition of the minerals are leading to the unfavorable properties. These factors however, are also connected to an agricultural term sodic soils.

Laboratory and field tests were carried out in order to get information about both the dispersive and sodic properties of the soil samples.

Laboratory test results showed that in many cases the dissolved salts and ionic composition of the minerals are leading to the unfavorable properties. These factors however, are also connected to an agricultural term sodic soils.

These are suggesting that there might be a relationship between the term “dispersive” and “sodic” soil. Not all dispersive soils are sodic and nor are all sodic soils dispersive, but there is an intersection between the two terminology (Fig. 13.).

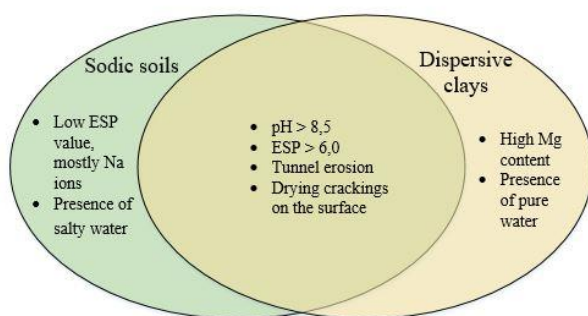


Figure 13. Relationship between dispersive and sodic soils

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