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Monitoring of collapsible soils in Slovakia

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Abstract: Collapse is an important factor in assessing the economy of construction foundation and security. Collapsible soils affect unfavourably the foundation of constructions and the environment, since the process of collapse causes significant volume changes as well as changes in the properties of soils. Collapse monitoring in foundation soil consists of several subsequent stages. In the beginning stages, collapsing sediment occurrences are identified. In the territorial units studied monitoring of unfavourable results of collapse is carried out, consisting of inventory and documentation of damaged objects. Based on a set of obtained data and information, areas with soils susceptible to collapse may be distinguished, determining their engineering geological properties, degree of susceptibility to collapse, as well distinguishing regions and sub-regions with same susceptibility to collapse.

Key words: collapse, collapsible soils, susceptibility to collapse, monitoring, damages to objects.

Introduction

Monitoring of collapsible soil is one of the subsystems of the "Partial monitoring system of geological factors" (KLUKANOVÁ, 1993), which is a part of "Environmental Monitoring of the Slovak Republic". The aims of geofactor monitoring are to investigate and evaluate the mechanism of origin and evolution of processes in natural environment, to foresee their evolution trends in time and space and to suggest measures to reduce negative effects of these processes.

Under the term "collapse", used predominantly in geotechnical literature and referring mainly to aeolian sediments,. we understand a sudden reduction of volume due to moisture and load. Soil collapse leads in many cases to a failure of foundations and damage to buildings due to uneven or excessive subsidence. Therefore, collapsible soils belong to unreliable foundation soils.

The large number of failures and break-downs in buildings caused by soil collapse in our country as well as abroad points to the fact that geotechnical problems of collapsible soils have not been paid due attention. On the other hand, in many cases foundations are designed with excessive security, or inadequately, although modern and expensive technologies are being applied. The choice of inadequate design may be affected by various circumstances. Meagre knowledge of physical and mechanical properties of foundation soils is one of the most serious causes. Other factors to mention are: unexpected presence of water, insufficient knowledge of the load of the building, or wrong use of technology.

The problems of collapse are in Slovakia even more aggravating due to the fact that aeolian sediments occur on an area of almost 7000 km^2 (ŠAJGALÍK, 1985), which is approx. 14% of the surface of the Slovak Republic (Fig. 1). From the above it follows that it is important to investigate and evaluate the mechanism of soil collapse, surface collapse manifestations, changes in the geological environment, to foresee their temporal and spatial effects and to take measures which would minimize these effects to an acceptable level.

Conditions and mechanism of soil collapse

A number of Slovak as well as foreign authors have studied the conditions and mechanism of soil collapse. According to STN (Slovak Technical Standard) 73 1001 "Foundation of structures. Subsoil under shallow foundations", collapse may occur if any of the following conditions has been identified:

- the soil is of aeolian genesis,
- the content of the silt component is more than 60 % of dry soil weight,
- the content of the clayey component is less than 15 % of dry soil weight,
- the saturation degree is less than 60 % and liquid limit is less than 32 %.

Among other conditions of collapse the above standard mentions porosity exceeding 40 % and simultaneous natural moisture below 13 %. As collapsible soils are classified those in which the collapse coefficient (I_{mp}) exceeds 1 %.

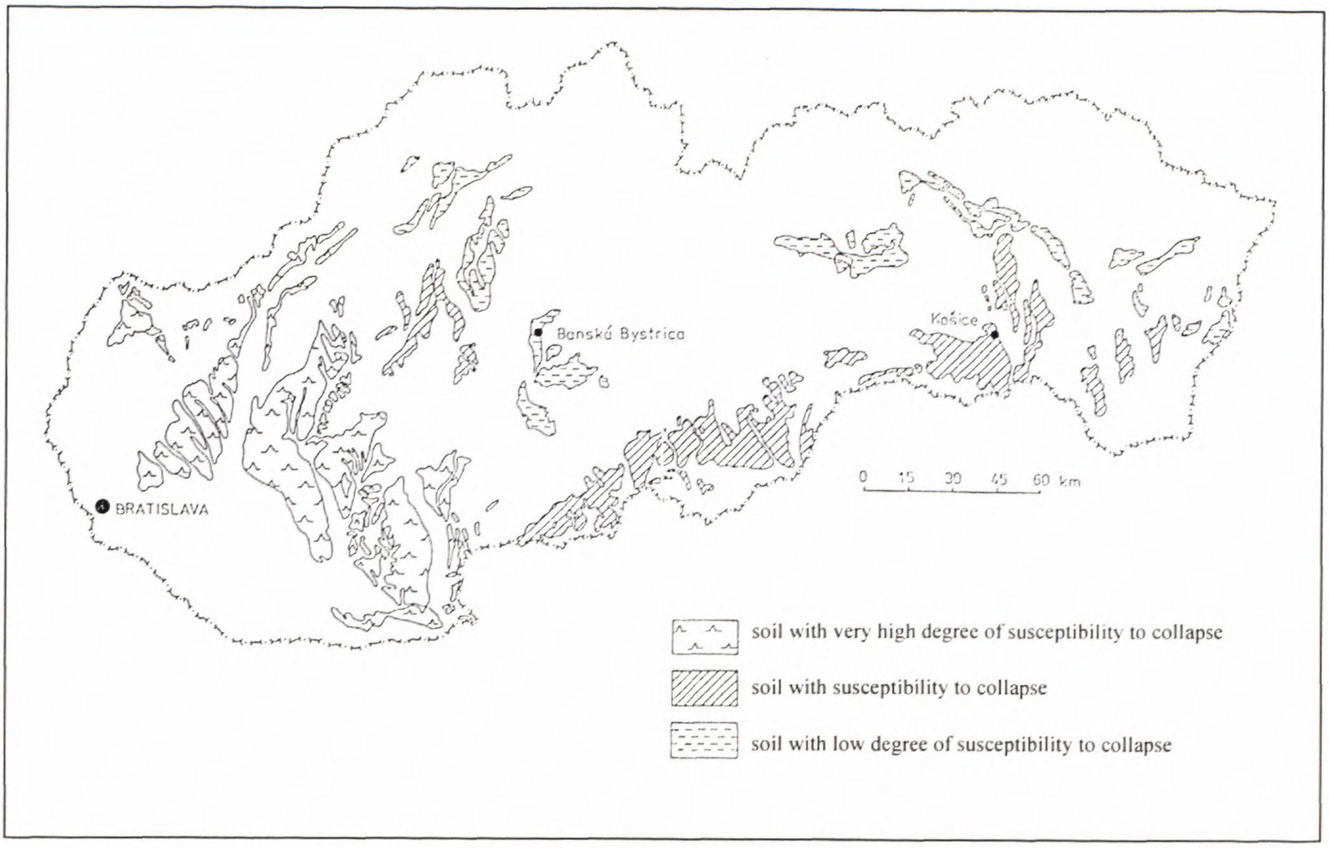


Fig. 1 Extend of collapsible soils in Slovakia. Map was compiled on the basis the work of J. ŠAJGALÍK, I. MODLITBA and A. KLUKANOVÁ

The causes of soil collapse are various. They are controlled by the genesis of soil, post-genetic processes, compactness of soil, hydrogeologic conditions, mineral composition etc. On the basis of microstructural analysis (KLUKANOVÁ, 1988) and the results of the work of ŠAJGALÍK and MODLITBA (1983), collapse may be divided into three phases, which, however, take place simultaneously.

In the first phase, the original microstructure is destroyed, due to increased moisture under external pressure. The increase of saturation degree in soil causes loss of capillary adhesion force and to a considerable extent it decreases the strength of clay bridges. The destruction leads also to damage of clay films covering sand or silt quartz grains, or other clastic minerals. Aggregates and micro-aggregates disintegrate as well. The intensity of carbonate dissolution and their migration in the soil increase.

In the second phase, the microstructure is disintegrating, which is reflected in the displacement of damaged clay films. Water, which causes also subsurface erosion, along with external stress affect, the transport of particles. Other important effects are: decrease of carbonate content, compressing of other fabric elements, decrease of the total volume of soil.

In the third phase, new micro-structure is formed after collapse. The soil acquires a heterogeneous structure, in contrast to the former homogeneous one, the basic structural units of the soil having disintegrated, i.e. individual grains are not perfectly covered by clay films any more and they are not connected by clay bridges. The per-cent content of individual pore-size fractions changes. The collapsed soils have lower percentage of pores with the size of up to 0.005 mm. The content of pores with a size of 0.005 to 0.01 is significantly higher. From the above facts it follows that the translocation of disintegrated clay films and bridges has a principal role in the soil collapse process (KLUKANOVÁ, 1988).

Characterisation of collapsible soils

There are several groups of collapsible soils. The two most important are:

- soils with a high degree of susceptibility to collapse. The collapse coefficient is higher than 3%. Among these soils are typical and sandy loess.

- soils susceptible to collapse. Their collapse coefficient ranges from 1 to 3%. Into this group belong aeolian sandy, clayey loess and a part of loess-like sediments described later.

Available results show that collapse depends above all on the fabric. Collapsible soil is composed of silt and sand grains covered by clay films, connected by clay bridges and clay buttresses. We assume that most susceptible to collapse is a soil having an exactly balanced ratio between the quantity of clay minerals and sand or silt grains, so that these grains are covered by clay minerals and connected by clay bridges. Clay minerals are not present in such fabric in any other form. Any variation from the balanced ratio between the two fractions (other form of clay mineral occurrence in the fabric) results in collapse. Any soil having above described fabric is collapsible at increased moisture and/or increased strain in the foundation soil. The degree of collapse is affected also by porosity (especially by pores with a diameter of about 0.01 mm), the contents of carbonates, oxides, hydroxides of metals (above all iron and manganese) and soluble salts. From the above it follows that the collapse process is very complex, depending on many factors, which are to a great extent variable.

From the viewpoint of geotechnical properties, collapsible soils have high strength under conditions of onstant natural moisture. After saturation with water, their strength rapidly decreases. The properties of these soils change significantly after collapse. Collapsible soils put higher requirements on geotechnical investigations than other foundation soils. Their characteristics, determined according to the results tests, are set out by the standard STN 73 1001.

Extensive investigations of the properties of collapsible sediments in previous years (KLUKANOVÁ et al. 1989, 1992, KLUKANOVÁ, 1988) allow us to characterize basic physical-mechanical properties of their various types and their variations.

Soils with a high degree of susceptibility to collapse

Among soils with a high degree of susceptibility to collapse are typical loess and sandy loess.

Typical loess is characterized by being non-bedded, primarily calcareous, having capillary porosity. It is generally dry, of yellow to dark-yellow colour with visibly predominant grain-size composition varying in the range of 20 - 63 μm, which corresponds to coarse-grained silt to very fine-grained sand.

The fabric consists exclusively of skeletal microstructure. The soil is very homogeneous and isotropic. Fig. 2 shows a micrograph of the fabric of a typical loess. The silt fraction is predominant. According to grain-size analysis, it is characterized by a high content of the silt fraction (65-72 %) and low content of the clay (7-17 %) and sand fractions (15-20%). The water content depends on the content of clay particles, which, due to their properties and the size of specific surface bind the predominant part of

Fig. 2 The micrograph of the fabric of a typical loess. Locality Mnešice brick-plant near Nové Mesto nad Váhom

water in the soil. The liquid limit, as a sensitive indicator of clay mineral content, is low as well. According to the liquid limit value and consistency index, we classify typical loess as low- to medium-plastic, with strong to hard consistency. The physical properties of loess sediments are listed in Tab. 1. The value of the collapse coefficient in relation to load is in Fig 3.

Tab.1 Physical properties of typical loess

Soil properties	Units	Average	Minimum	Maximum	Variance
Moisture content	%	9,955	5,391	14,900	3,119
Grain-size fraction < 0,002 mm	%	10,720	6,750	17,010	3,686
Grain-size fraction 0,002-0,06 mm	%	68,226	65,020	72,130	2,469
Bulk density of moisture soil	kgm^{-3}	14,564	1,399	15,070	2,514
Bulk density of dry soil	kgm^{-3}	13,788	1,337	14,207	2,137
Specific density	kgm^{-3}	26,956	26,570	27,329	1,324
Plasticity limit	%	24,044	22,300	24,906	0,509
Liquid limit	%	30,833	29,900	31,517	0,499
Pore content	%	46,900	44,500	50,850	2,286
Saturation degree	%	24,039	10,095	40,830	5,920
Carbonate content	%	13,828	6,750	19,790	1,827
Organic mater content	%	1,637	1,268	2,004	0,187

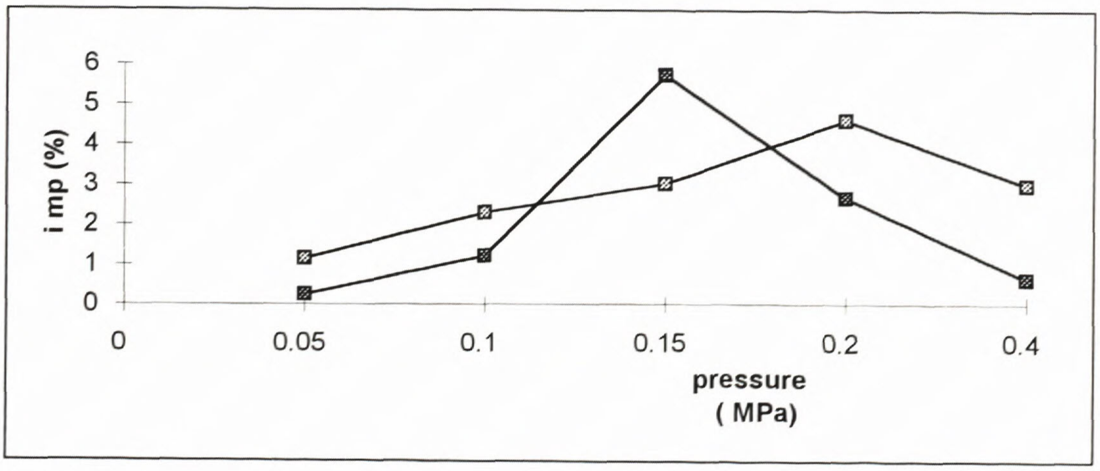


Fig. 3 Relationship between the collapse coeficient i_{mp} and load pressure for soils with high degree of susceptibility to collapse.

Sandy loess is mostly non-bedded, or there is fine bedding. Usually they are slightly calcareous, less porous than typical loess, having similar colour. This type of loess is characterized by a mixture of grains with sizes of 2 - 60 μm and 200 - 500 μm, which corresponds to fine-grained to medium-grained sand. The fabric is very similar to typical loess. The soil formed by aeolian transport, but the source areas had different rock composition than those of typical loess. Fig. 4 shows a micrograph of the fabric of sandy loess. Grain-size analysis revealed clay fraction contents of 7.38 to 9.43 %, silt of 35.34 to 40.00 % and sand fraction contents of 52.4 to 54.7 %. The higher content of sandy fraction to the detriment of clay results in lower moisture, lower plasticity limit values etc. Moisture at liquid limit varies from 23.8 to 24.71 %, at plasticity limit from 20.68 to 21.26 %. According to liquid limit and consistency index, we classify the soil as low-plastic, with hard consistency. The content of carbonates has been determined as 5.58 to 11.57 %. Physical properties of sandy loess are listed in Tab. 2.

Collapsible soils

Among collapsible soils we classify aeolian sands containing clay fraction, some clay loess and loess-like sediments. The value of the collapse coefficient I_{mp} for collapsible soils in relation to the size of load is shown on Fig. 5.

Aeolian sands are medium-grained, with typical good sorting and rounding of quartz grains, sometimes also of carbonates. The fabric is character

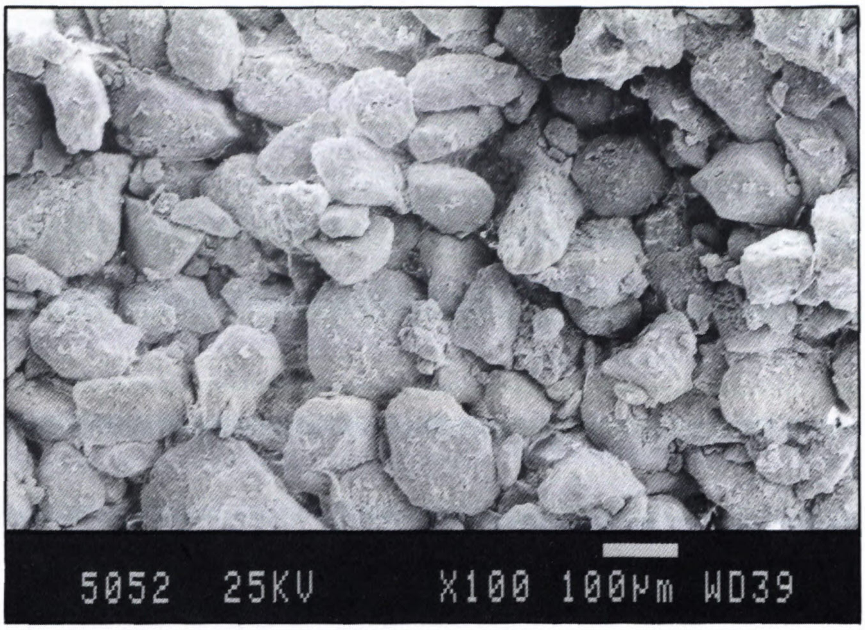


Fig. 4 The micrograph of the fabric of a sandy loess. Locality brick plant Hajnačka

Tab. 2 Physical properties of sandy loess

Soil properties	Units	Average	Minimum	Maximum	Variance
Moisture content	%	4,404	3,350	5,170	0,696
Grain-size fraction < 0,002 mm	%	6,453	7,380	9,430	2,195
Grain-size fraction 0,002-0,06 mm	%	37,730	35,340	40,000	2,001
Specific density	kgm^{-3}	27,295	27,270	27,410	7,263
Plasticity limit	%	21,032	20,680	21,260	0,214
Liquid limit	%	24,196	23,800	24,710	0,347
Pore content	%	37,700	31,120	39,210	2,786
Carbonate content	%	9,081	5,580	11,570	2,505

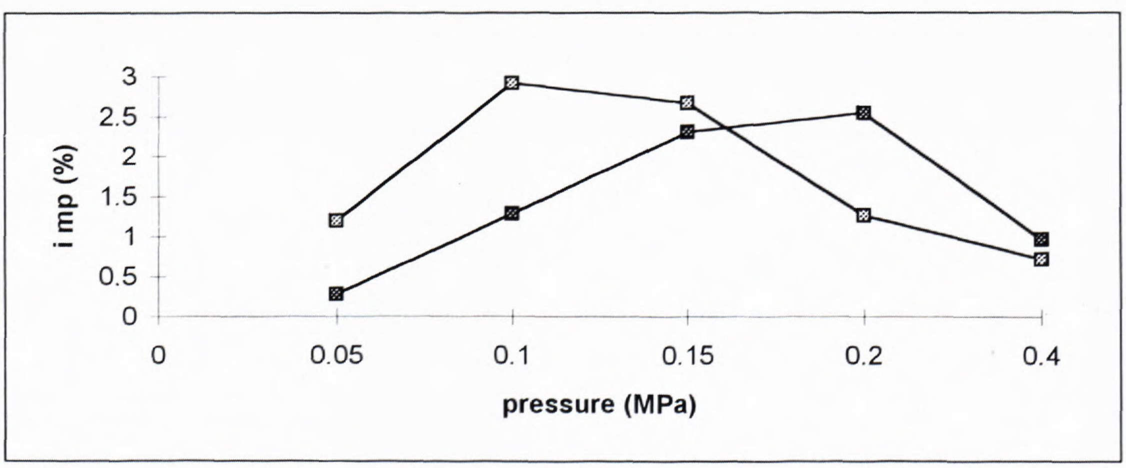


Fig. 5 Relationship between the collapse coefficient i_{mp} and load pressure for collapsible soils

ized by exclusively skeletal type of microstructure. Natural moisture of these soils is relatively low, it attains an average of 8.08%. According to grain-size analyses the clay fraction forms 4.02 to 9.57%, silt fraction 24.32 to 28.38% and sand 65.9 to 77.83%. The moisture at liquid limit varies from 24.2 to 24.7 %. Fig. 6 shows a micrograph of aeolian sand fabric. Their physical properties are listed in Tab. 3.

Clayey loess is non-bedded, low-porous. Its content of carbonates and its colour are similar to typical loess. The greatest percentage display silt particles of a grain-size ranging from 20 to 60 μm, and the clay faction is in the range of 25 to 30%, with a grain-size of 2 μm. Clayey loess has a matrix, skeletal-matrix to matrix-laminar microstructure. Collapsible are however only soils having skeletal-

Tab.3 Physical properties of eolian sand

Soil properties	Units	Average	Maximum	Minimum	Variance
Moisture content	%	8,078	6,770	9,570	1,019
Grain-size fraction < 0,002 mm	%	4,910	4,020	6,230	0,865
Grain-size fraction 0,002-0,06 mm	%	26,010	24,350	28,380	1,698
Bulk density of moisture soil	kgm^{-3}	18,070	16,800	19,500	0,111
Bulk density of dry soil	kgm^{-3}	16,270	15,400	16,800	0,062
Specific density	kgm^{-3}	26,925	26,900	27,000	0,004
Plasticity limit	%	19,900	19,200	20,600	0,700
Liquid limit	%	24,700	24,200	25,200	0,500
Pore content	%	39,573	37,780	42,751	2,342
Saturation degree	%	33,210	27,596	37,608	4,998
Carbonate content	%	4,000	1,010	7,030	2,898

Tab. 4 Physical properties of clayey loess

Soil properties	Units	Average	Maximum	Minimum	Variance
Grain-size fraction < 0,002 mm	%	32,660	25,010	37,600	4,246
Grain-size fraction 0,002-0,06 mm	%	50,386	48,800	51,300	0,824
Specific density	kgm^{-3}	27,410	27,390	27,440	1,915
Plasticity limit	%	25,448	22,360	30,130	2,573
Liquid limit	%	42,541	39,710	55,720	5,404
Pore content	%	35,875	34,100	37,250	1,403
Carbonate content	%	1,000	0,700	1,120	0,156

Tab. 5 Physical properties of loess-like sediments

Soil properties	Units	Average	Maximum	Minimum	Variance
Grain-size fraction < 0,002 mm	%	16,010	10,230	17,123	4,819
Grain-size fraction 0,002-0,06 mm	%	62,090	55,680	63,234	2,111
Specific density	kgm^{-3}	26,450	26,350	26,740	0,125
Plasticity limit	%	16,100	15,890	20,600	1,205
Liquid limit	%	27,400	24,870	33,300	2,229
Pore content	%	31,300	30,320	40,810	4,300
Carbonate content	%	1,944	0,897	2,520	0,511

matrix type of microstructure. Fig. 7 shows a micrograph of the fabric of a clayey loess.

According to grain-size analysis, the soil contains 38 % of clay, 51 % of silt and 11 % of sand fraction. The liquid limit according to Attenberg is 56 %, plasticity limit is 30 %. According to liquid limit and consistency index I_c = 1.7, we classify the soil as highly plastic, with solid consistency. The carbonate content is 1.1 % and the content of organic matter 4 %. Physical properties of these soils are listed in Tab. 4.

Loess-like sediments are represented by a large group of soils with different mineral and grain-size composition. Some physical properties are listed in Tab. 5. It is aeolian material, resedimented due to various secondary processes (allochtonous loess-

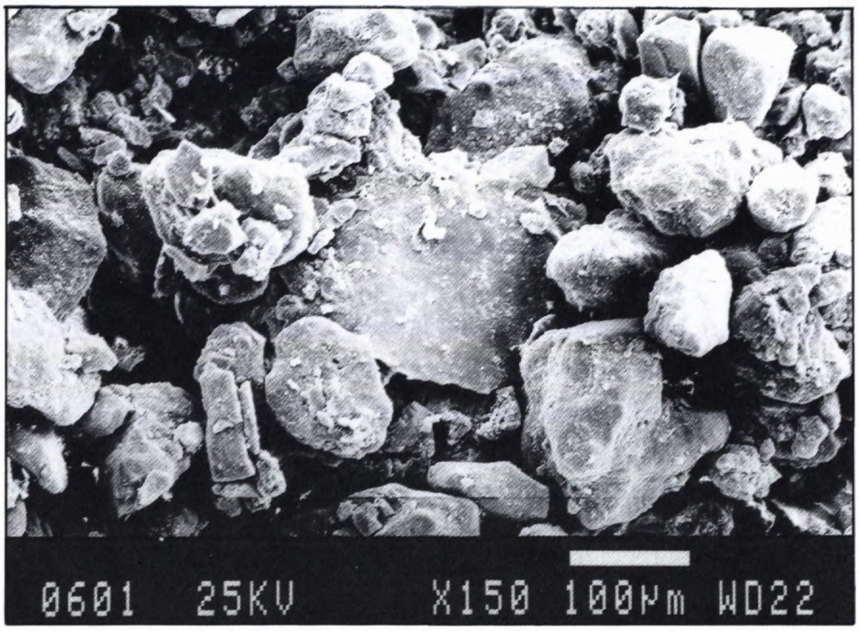


Fig. 6 The micrograph of the fabric of a aeolian sands containing clay fraction. Locality Bajč.

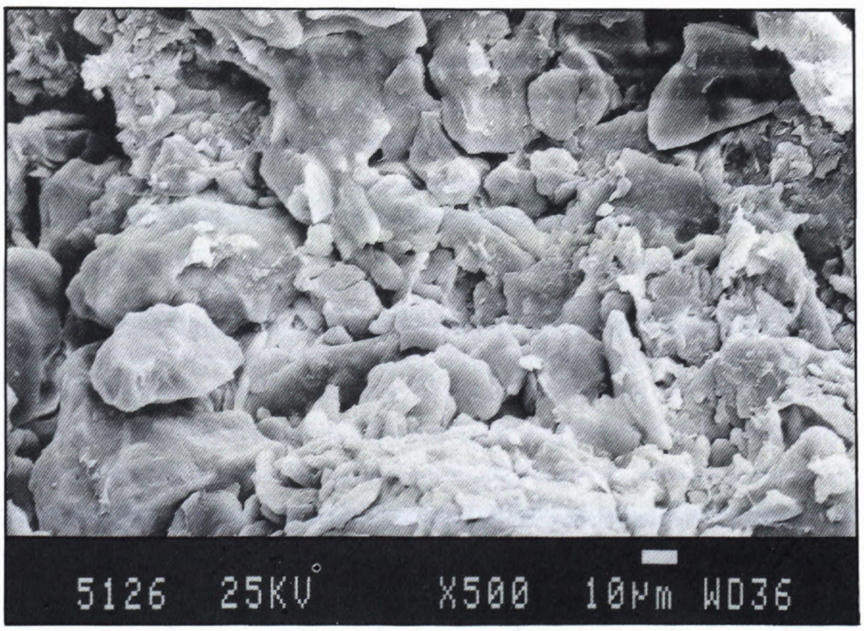


Fig. 7 The micrograph of the fabric of a clayey loess. Locality Jesenské.

like sediments) or changed in situ (autochtonous loess-like sediments), or it is non-aeolian material, in which the process of loessification took place. In place of loessification there is often loamification or gleyfication. The most important secondary processes taking place during resedimentation are:

- deluvial, colluvial processes and solifluction, due to which slope, deluvial and solifluction loess is formed,
- fluvial and proluvial processes - fluvial and proluvial loess,
- changes caused by cryoturbation - cryoturbational loess,
- eluvial and pedogenetic processes - give the origin to loess.

Loess-like sediments may have formed either from typical, sandy or clayey loess. Their porosity is lower than in the original material. A great change is observable, concerning the contents of carbonates. Some of these soils are totally without carbonates. They differ also in colour. Loess-like sediments may be characterized on the micro-scale only with difficulty, since they are strongly heterogeneous having anisotropic fabric. Heterogeneity is enhanced also by the occurrence of several basic microstructure types (matrix, skeletal, laminar as well as honeycomb etc.). Prone to collapse are however only those which have skeletal and skeletal-matrix type of microstructure. Fig. 8 shows a micrograph of the fabric of a loess-like soil.

Monitoring of collapsible soils

Among best ways of characterizing regional occurrence of collapsible soils is monitoring of their unfavourable results, i.e. damage to objects. An inventory of damaged objects was started to be taken on the territory of East Slovak Lowlands, Búčske Terraces, lower flow of the river Hron. We shall proceed towards the Southern Slovak Basin, Trnava and Nitra Hills. Failures are recorded in a specially designed inventory form (Fig. 9). The documentation of specific failures is aimed at most damaged construction parts, there are characterized the failures, the age of the object, the depth of foundations, type material used for the construction of the building, factors affecting the extent of damages, or repair work.

The investigation of the extent of damages to buildings is carried out on selected objects, in regular intervals - twice in a year - especially as far as the state, number and width of failures on objects are concerned, determined by indirect measurement of failure openness. The number and size of failures are then evaluated in time and space.

Engineering geological properties of soils are determined on undisturbed soil samples taken from boreholes, pits and outcrops near the object. The samples are tested in the engineering geology laboratory at the Doinýz Štúr Institute of Geology in Bratislava. First of all there are investigated moisture, plasticity, grain-size composition, bulk and specific density, saturation degree, contents of carbonates and organic matter. Besides this, mineral and chemical composition, as well as the fabric of soils, especially its changes caused by collapse, are studied as well, using an scanning electron microscope. The susceptibility to collapse of these soils is monitored as well using collapse test not only in oedometer, but also in a triaxial chamber.

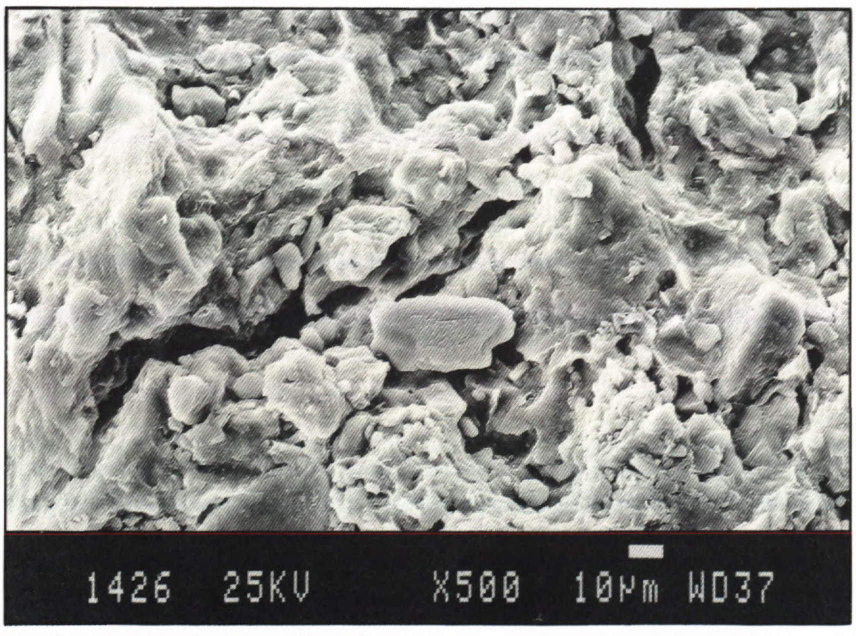
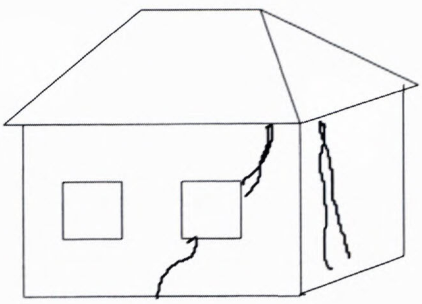


Fig. 8 The micrograph of the fabric of a loess-like sediment

Geomorphological unit: Podunajská pahorkatina - hilly land

District	Municipal	Street	Number	Type of object
NZ	Pohronský Ruskov	Pri kostole	8	family house

Outline-photo 3/21, 22 D1/12



Description of failure

Damaged pipe led to an intense penetrating of surficial water into the subgrade. Joints (cracks) are wide locally up to 10 cm.

Groundwater level

assumed – 2.0 m

bored:
stabilised:

Profile of foundation soil

0.0 -0.5m soil horizon
0.5 - loess sediments

Type of foundations

flat foundations, no cellar

Depth of foundations: 0.60 m

Characteristics of failure

Date	Type of change	Side of object	dip	Width	Length	Cause of failure	Environmental impact
		side	75	10 cm	3 m	sudden increase of moisture (w)	no
		front	45	10 cm	2 m	sudden increase of w	

Fig. 9 Inventory of failure of building

The output is a data bank, containing data on the degree and character of damages to an object, their development in time, about conditions at foundation of the object and causes of the collapse process etc. The inventory is complemented by a map on the scale 1 : 10 000, or 1 : 50 000, showing the extent and intensity of collapse processes on the territory studied, as well as an evaluation of the time course of the monitoring, with an interpretation of the measured data. The data bank with data on the occurrence and intensity of collapse processes will be adjusted for data input into a partial information system.

Causes of damages to objects

Among principal factors causing damages to objects are increased load and moisture, due to water infiltration into foundation soil. The source may be: damaged water piping, sewers, drain pipes or excessive precipitation. Moisture increase causes deterioration of geotechnical properties of foundation soil, decrease of its loading capacity, large deformations of constructions due to irregular or excessive subsidence of foundations. The occurrence of failures in buildings, foundations as well as supporting upper parts of building may be caused also by incorrect calculation of foundations of the building itself, or by a change of loading (e.g. by load concentration transferred from the neighbouring object, dynamic effects from a road or railway with high transport intensity).

Map of the susceptibility of soils to collapse

One of the most important outputs is the construction of maps of the susceptibility of soils to collapse. It is compiled by the method of engineering geological zoning. Zones and sub-zones are distinguished having the same susceptibility to collapse. The method applied in the compilation of the map corresponds to the proposed manual for the compilation of engineering geological maps of geofactors of the environment (KLUKANOVÁ et al., 1995). By the traffic-light method we mark homogeneous territorial units - zones and sub-zones with the same susceptibility. Green represents territories not susceptible to collapse, orange are territories susceptible to collapse and red are territories with very high susceptibility to collapse. Criteria for distinguishing the zones have been described in the above manual.

Fig. 10 shows the map of the susceptibility of soils to collapse on the scale 1 : 50 000 from the area of Búčske Terraces.

Conclusion

The aim of monitoring is to investigate changes in the observed characteristics, an analysis of relationships between these changes, a prognosis of the development of these processes, the verification of the reliability of prognoses in practice as well as a generalization of information in relation to territories with the same geological structure and other conditions of natural environment.

The paper refers to two groups of soils with different susceptibility to collapse: soils with a high degree of susceptibility to collapse and soils susceptible to collapse. In the first group there are typical loess and sandy loess. To soils susceptible to collapse belong aeolian sands, clayey loess and loess-like sediments with skeletal and skeletal-matrix microstructure. The character of their fabric affects the engineering geological properties and their changes due to environmental changes.

Monitoring of collapsible soils belongs to the most accurate ways of characterizing the results of collapsible soil occurrences. The aim of monitoring is to follow and evaluate the mechanism of soil collapse, its surface manifestations and negative changes in the geological environment, its destruction, to foresee the effects of these changes in time and space and to bring about measures which would reduce unfavourable effects of collapse to an acceptable level. The result should be input data used for finding solutions to the problems of environmental protection and optimisation of exploitation of the geopotential in the country.

Within the first stage of monitoring, an inventory of damaged objects is taken in the form of an evaluation of the unfavourable results of soil collapse. When documenting specific damages, the most damaged constructional parts are registered, the damages are characterized, as well as the age of the object, depth of foundations, type material used for the construction, factors affecting the extent of damages, or repair work. Further work will lay in permanent observation of changes of damages on selected objects, as well as of changes in soil properties.

A special kind of generalization of the results of the partial monitoring system is the evaluation of susceptibility of the territory to soil collapse, expressed in cartographic form as a map of the susceptibility to soil collapse, in which there are evaluated pre-defined geological regional units. The map is constructed by the method of engineering-geological zoning. Zones and sub-zones are distinguished, having the same susceptibility to collapse, i.e. the zone of territory not susceptible to collapse, the zone susceptible to collapse and zone of territory with very high susceptibility to collapse.

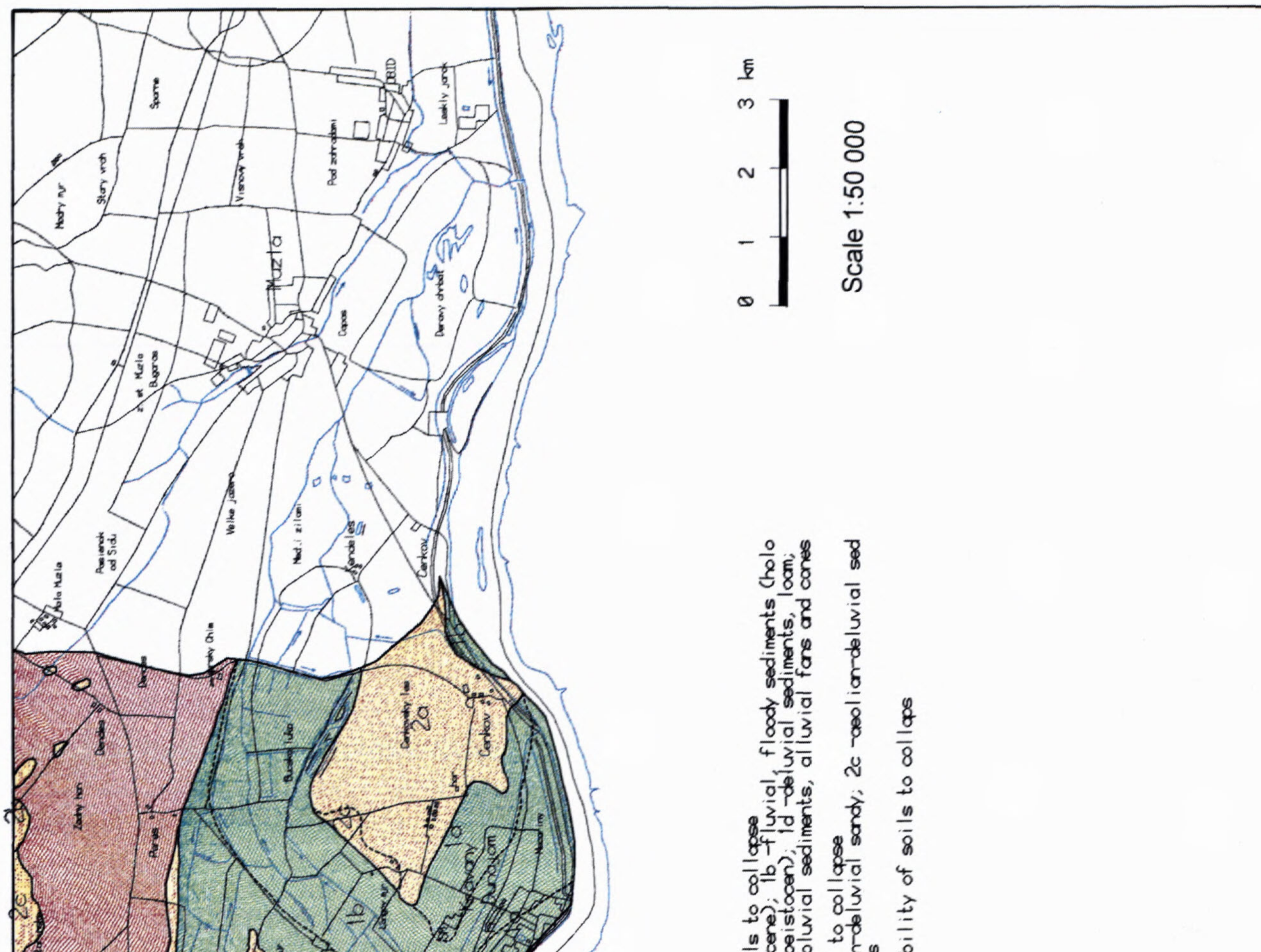


Fig. 10 Map of susceptibility of soil to collapse

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