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DETERMINATION OF CONSOLIDATION CHARACTERISTICS OF ROCKMASS ON THE BASIS OF WATER LEVEL AND SURFACE SUBSIDENCE OBSERVATIONS

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SUMMARY

The most significant area of surface subsidence in Hungary caused by withdrawal of underground water is the depression area due to mine dewatering around open-pit lignite mines of Upper-Pannonian layers at Matraalja. The decrease in water level and the resulting pressure drops are monitored by observation wells since 1961 and the surface movements occuring as the indirect effect of dewatering are monitored by the geodetic levelling of a surveying net. The paper presents the evaluation of the time logs of the observation data, the determination methods of the consolidation characteristics necessary for the computer prediction model of the subsidence process and the values of the consolidation characteristics obtained in the course of evaluation and pertaining to the area under investigation.

INTRODUCTION

The most important occurrence of surface movements entailed by water withdrawal in Hungary is in the area of the Upper-Pannonian open-pit lignite mines at Matraalja (Figure 1). The preliminary dewatering of the open-pit mining territory was begun in 1961 and lasted until 1984 in the open-pit mine East-I. Intensive water drainage for the purpose of water protection has been performed in the Western area since 1970 and in the area East-II since 1980. In the course of the water protection activities from 1961 to the end of 1993, approximately 460 million m^3 of water was produced from the system drained and having a depth of about 200 m with a maximum of 13 water-bearing layers. In more than 3 decades of drainage, the depression area of the underground water-bearing layers came to cover an area of appr. 900 km^2. The time logs of the regional water level decrease are monitored by a group of observation wells suitable for layer by layer monitoring and of increasing number.

Figure 1 Site Location

Monitoring the subsidence resulting from drainage is performed by the geodetic calibration of the points of the surveying net twice a year. The basic points of the surveying net were laid in 1955, the net was developed between 1970 and 1973 and its length reached approximately 80 km by the end of 1993.

Processing the observed data of water level was performed by plotting water level time legs for each water-bearing layer and - by using a seepage hydraulic computer model by constructing water level isolinear maps.

The subsidence data were processed by plotting the subsidence and subsidence rate time logs and by the computer-aided regression equalisation of the time functions. For that purpose the surveying net was divided into sections and the average values of section measurement points were related to the centres of gravity of the sections. The processing results were used to determine the consolidation parameters necessary for the prediction model of land subsidence in the way described below.

DETERMINING THE DELAY TIME OF THE SUBSIDENCE PROCESS

According to the evidence of the water level decrease and land subsidence time logs, land subsidence is not simultaneous with the water level decrease but began a few years later, i.e. with a delay.

The delayed appearance of subsidence is due to the pre-consolidation effect influencing the system storing surface water in the course of sedimentation. During sedimentation, the slowly subsiding area was first covered with alluvial deposit, than an emergence process took place simultaneously with denudation, while the rock mass remained in a state of consolidation corresponding to nearly its maximum load. The conclusion drawn from the observation data is in harmony with the geological and tectonical findings relating to the area: e.g. Ronai (1973; 1986) described the emergence of the area with and extent of 100-200 m on his map in the works analysing the crustal structure movements in the Quarternary.

The phenomenon is known from literature as well: e.g. the results of Helm (1984) in areas of California, according to which the critical water level decrease varied between several meters and several tens of meters, while the delay varied between 5 and 13 years.

Taking into consideration the fact that the time process of the water level decrease took various forms in the different water-bearing layers of the multi-layered system and at the same time the subsidence appeared as the cumulative effect, the relationship between the average depression (increase in effective stress) and the subsidence as cumulative effect was studied in order to find the value of the critical average water level decrease where the pre-consolidated matter begins to consolidate repeatedly.

By plotting the relationship between the measured subsidence and average depression regardless of the values of the initial, most uncertain period of subsidence - the value belonging to zero depression of the straight line marking the flexible section can be considered to be the threshold value (Δh_{crit}) due to pre,-consolidation. In the area under investigation Δh_{Crit} varies in the range of 15-20 m (Δ_{crit} = 1.5-2.0 bar).

As in the near surface layers consolidation begins at lower depression than that, further calculations were performed by accepting value Δh_{Crit} = 15 m. Thus the delay of the beginning of subsidence was found to be 4-5 years.

In the period of increasing load a clearly flexible behaviour is not contradicted by an increasing strain at a decreasing load - beginning recharge in the water-bearing layers. The reason for that is that two physical processes of conflicting tendency prevail in the multi-layered system of varied geological structure: in the thinner and/or more permeable impermeable layers as well as in the permeable layers of the system which consolidate only to a small extent but rapidly, the completed non-permanent strain enables the beginning of flexible expansion in correspondence to the pressure increase measurable in the observation wells; on the other hand, the thickest and/or least permeable layers continue to consolidate as a result of the excess pore pressure not yet balanced in them. In the process appearing on the surface cumulatively, the consolidation of the thick and/or least permeable layers prevails at a rate modified in accordance to the load. The value of strain appearing under load is a function of the thickness of the consolidating system and of its rock physical parameters.

DETERMINING THE VOLUMETRIC COMPRESSIBILITY OF THE ROCK STRUCTURE

The relationship (ε) of the water level decrease (Δh) and subsidence (s) i.e. subsidence projected on unit thickness of the consolidating layer, i.e. vertical strain can be used for determining the flexible volumetric compressibility of the consolidating rock structure (m_v) on the basis of the following relationship relating to the flexible rock mass:

$$S_{kr} = \frac{\Delta s}{\Delta h} = \frac{1}{tg\alpha} \qquad [-] \qquad (1)$$

$$S_{krf} = \frac{\Delta S}{\Delta h \,.\, H} = \frac{\varepsilon}{\Delta h} \qquad \left(\frac{1}{m}\right) \qquad (2)$$

$$\Delta\sigma' = \Delta h.\, \rho_v \,.\, g \qquad \left(\frac{N}{m^2}\right) \qquad (3)$$

$$m_v = \frac{S_{krf}}{\rho_v \cdot g} \qquad \left(\frac{m^2}{N}\right) \qquad (4)$$

The values of volumetric compressibility calculated for the centres of gravity of the observation sections are summarised in Table 1. A flaw of the method is that due to the specific siting of the surveying net it was impossible to determine the total thickness of the consolidation layers of the structure affected by the drainage by means of geological sections.

Table 1: Values of volumetric compressibility calculated from the measured data of depression and subsidence

Observation section	S_{kr} [-]	Consolidating Thickness [m]	m_{v2} 10^{-5} [m^2/N]
Visonta- 1	4. 00 10^{-3}	47	8.50 10^{-4}
Visonta-2	2.63 10^{-3}	47	5.60 10^{-4}
Visonta-3	2.70 10^{-3}	47	5 75 10^{-4}
Visonta 1-3	3 13 10^{-3}	47	6.67 10-4
Visonta 4	1.25 10^{-3}	54	2.3 1 10^{-4}
Visonta 4-5	9.83 10^{-3}	54	1.82 10^{-4}
Visonta 1-5	5.67 10^{-3}	52	1.09 10^{-4}
Halmajugra 1-3	1.19. 10^{-3}	108	1.10 10-4
Halmajugra 3-4	2.14. 10^{-3}	92	2.33 10^{-4}
Halmajugra 1-4	1 .78. 10^{-3}	94	1.89 10^{-4}
Range		47-108	11x10^{-4}-2.31x10^{-3}
Visonta average		50	1. 12 x 10^{-3}
Halmajugra average		98	1.77 x10^{-4}

DETERMINING THE DURATION OF THE PRIMARY CONSOLIDATION PHASE

According to the above, subsidence continues in the period of the water level regeneration as well, at a steadily decreasing rate. By means of the processing method presented in Figures 2-3, if the thickness of the consolidating layers and their seepage factor are known, it is possible to determine the time in which the primary consolidation reaches 93 % of its maximum value:

$$\tau = \frac{S_{krf}\,[H/2]^2}{K} \qquad (5)$$

$$T' = \frac{K.\tau}{m_v . \rho_v \, [H/2]^2} \qquad (6)$$

Time factor T' is analogue with Terzaghi's dimensionless consolidation time factor, to T = 1 value of which the 97 % consolidation of the consolidating layer bordered by porous layers on both sides belongs. Using the value S_{krf} as seen in Figures 2-3, the average seepage factor 4.54 x 10^{-11} m/sec obtained from the grain composition studies measured in the laboratory, and maximum consolidation layer thickness H = 30 m, τ = 9-29 years was calculated.

According to Taylor (1948), if there is a change in the liquid pressure before time τ, maximum subsidence does not necessarily reach the final value estimated from hmax, as a result of the prevailance of the dual process described above. The effect of the dual process was taken into account by moderating the consolidation factor CV calculated from the observ,ation data but also obtained by the evaluation of the curves $\sigma - \varepsilon$ obtained by Kezdi (1971) in an oedometer experiment as initial data, which determines the consolidation rate:

$$C_V = r c_V^V \qquad (7)$$

where

C_V^V = consolidation factor valid at the beginning of the recharge process

r = reduction factor expressing the effect of the recharge slowing down seepage and appearing due to the change in the hydraulic gradient at the border of impermeable-permeable layers

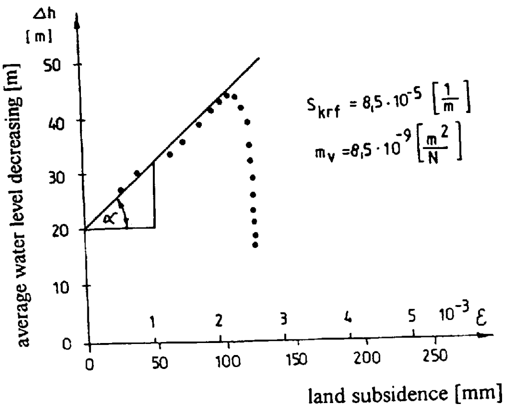

Figure 2. Relation between the average decrease of water level and the land subsidence (Visonta-I. monitoring section)

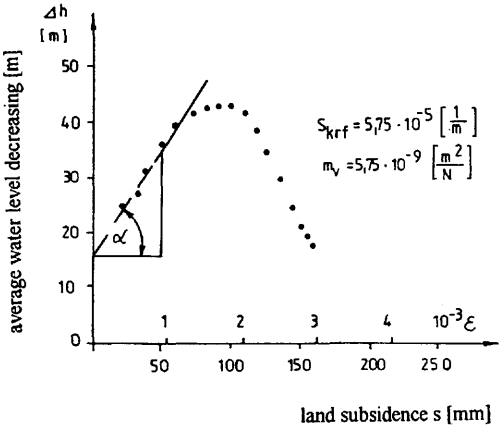

Figure 3. Relation between the average decrease of water level and the land subsidence (Visonta-3. monitoring section)

Reduction factor r was determined as having a value of 0.8 by plotting the observation time legs relating to the centres of gravity of each section of the surveying net at Visonta. Keedwell (1984) pointed out that permanent (plastic) deformation due to grain rearrangement begins together with primary consolidation, its significance is, however, subordinate in the dlssipatlon process of excessive pore pressure and suggested the separation of the two processes from a relationship expressing the connection between subsidence and the square root of time.

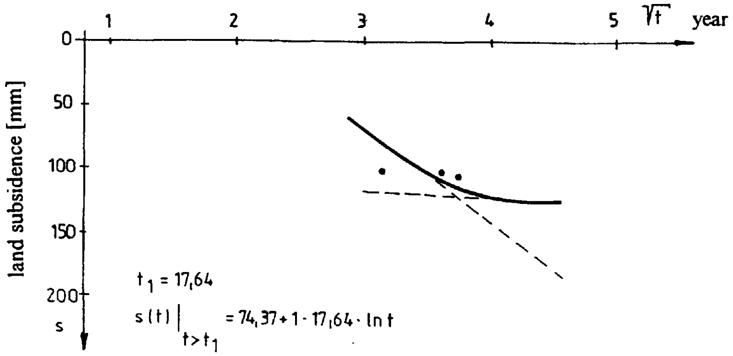

Figure 4. Margin of the primary and secondary consolidation (Visonta-l. monitoring section)

That relationship was used to determine the time of the filtering phase (Figures 4-5). It grave the time of flexible consolidation of the Visonta area due to drainage to be 17-24 years, depending on the distance from the drained pit, the depression and the extent of subsidence caused.

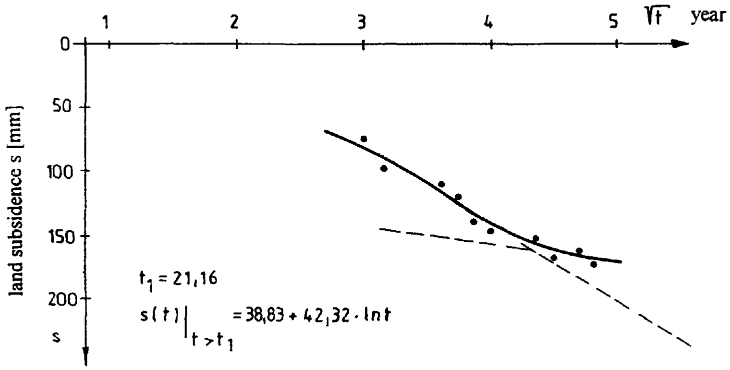

Figure 5. Margin of the primary and secondary consolidation (Visonta-3. monitoring section)

In the area of Halmajugra the water level decrease in the open-pit mine East II started a repeated consolidation, therefore the primary consolidation did not come to an end, furthermore it was quickened by the water level decrease following a temporary water level increase.

Using Poland's theory (1984) - according to which "if pore pressure is balanced in the consolidating Impermeable layers by that in the boundary permeable layers, consolidation comes to a stop (end of the flexible phase), the rate of subsidence/pressure decrease will become a true measure of the original compressibility of the system, if the water level is the average level of the permeable layers of the consolidating structure" - the volumetric compressibility values were again calculated with the values of subsidence read at the end of primary consolidation on the graphs and that ofthe average depression reduced by 15 m (pre-consolidation load):

$$S_{kr} = \frac{s}{\text{consolidating thickness (average depression}^{max} - 15)} \qquad (8)$$

Comparing the data summarised in Table 2 with the values obtained from the linear initial sections of graphs h - ε, an agreement exceeding the accuracy of laboratory measurements was to be found.

Table 2: Calculated volumetric compressibility based on subsidence after primary consolidation and average depression reduced by pre-consolidation stress (15 m)

Area	S primer	Total thickness of Clays [m]	Maximum average depression [m]	S'krf [m^{-1}]	m_v [m^2/N]
Visonta-l	126	47	44	9.24 x 10^{-5}	9.24 x 10^{-4}
Visonta-2	143	47	44	1.05 x 10^{-4}	1.05 x 10^{-3}
Visonta-3	168	47	43	1.28 x 10^{-4}	1.28 x 10^{-3}
Visonta-4	238	54	30	2.94 x 10^{-4}	2.94 x 10^{-3}
Visonta-S	200	54	38	1.61x 10^{-4}	1.61 x 10^{-3}
Visonta 1-3	150	47	44	1.07 x 10^{-4}	1.07 x 10^{-3}
Visonta 4-5	198	54	34	1.93 x 10^{-4}	1.93 x 10^{-3}
Visonta 1-S	175	52	40	1.35 x 10^{-4}	1.35 x 10-3
Range					9.24 x 10^{-4} -2.94 x 10^{-3}
Average					1.52 x 10^{-3}

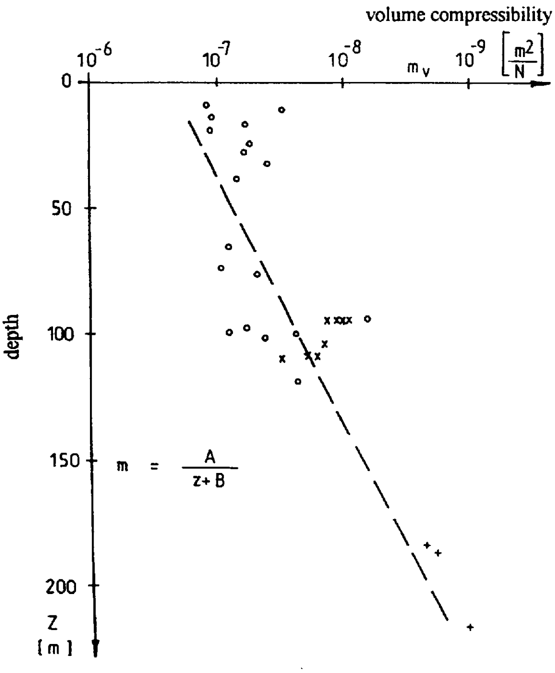

Figure 6. Relation between the volume compressibility and the depth of consolidating layers

Figure 6. shows the values of volumetric compressibility obtained by the evaluation described above of the observation data and those measured in the laboratory according to depth. The figure displays the applicability of the information obtained by the evaluation of the observation data for the purpose of a subsidence prediction model in spite of the undeniably limited number of the rock physical parameter values under investigation.

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