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ANALYSIS OF LOCAL VARIABILITY OF OVERBURDEN PHYSICAL AND MECHANICAL PROPERTIES AS A METHOD FOR ASSESSING KARST HAZARD

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ABSTRACT

The technique of karst hazard assessment used on the territory of Ust-Kishert village is presented in the paper. We analyse the parameters of the research area natural structure which is characterized by the abundance of carbonate-sulphate karst. In this work, we consider karst rock mass as a certain volume of geological space occupied by the karstic rocks and the overburden (i.e. overlapping sediments) that are affected by the karst process.

The purpose of this study is to identify the areas of local changes of overburden physical and mechanical properties relative to the background level. We consider such areas as the sites of the most probable location of the weakened zones in karstic rocks. The working hypothesis of the investigation is as follows: the physical and mechanical properties of the overburden vary over the-weakened zones in the karstic rocks. These local changes depend on the degree of hydrogeological activity of the karst cavity and on its vertical dimensions.

The condition and the strength properties of the overburden sediments can serve as the indicators of weakening of the rock mass. We used this idea for the integral analysis of physical and mechanical properties to construct the cartographic model of karst hazard assessment. We then compare this model to the one proposed earlier

Keywords: karst, karst hazard, overburden sediments

INTRODUCTION

Surface karst forms result from subsidence of karstic rock masses, or their partial or complete collapse into the weakened zones at the depth. They have spontaneous occurrence and significantly complicate economic development of the territories. Moreover, sinkholes in contrast to the depressions, develop very fast which makes it impossible to take the necessary measures for averting the damage to the buildings, if there were made no protective constructive measures.

In this work, we consider karst rock mass as a certain volume of geological space occupied by the karstic rocks and the overburden (i.e. overlapping sediments) that are affected by the karst process. Exploration of the overburden can be increased in accuracy when held within the framework of an integral karstological forecast based on

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the comprehensive assessment of the qualitative karst hazard treats [5]. Another way of increasing the accuracy is by raising the number of factors considered.

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Under the conditions of non-equilibrium state caused by the formation of cavities in the karst rock mass, the overburden appears to be a typical dissipative system capable of evolving and creating ordered structures (in this case, deformation ones) determined by the self-organization of the geological medium [2]. Thus, it is hard to escape the conclusion that the formation of a karst cavity in the karstic rock mass leads to a change in the condition and the mechanical properties of subsoil in the roof of the cavity. The stress relief at the weak point of the karstic rock mass causes this with the overburden being deformed and a sinkhole being formed on the ground surface.

In this study, we associate karst cavities and crushed zones with weakened elements and consider them as the areas of disintegration of karstic sediments, characterized by increased fracturing and weathering, often to a state of rock flour. The development of cavities in the formation affects its natural stress field, thus initiating such deformations as protrusions towards the empty space or collapse of the arch of the cavity with possible creation of the hole on the surface.

SHORT CHARACTERISTICS OF THE RESEARCH AREA

The investigated rock mass is situated in predominantly gypsum and carbonate-gypsum karst area [3] of the Kishert district in Perm region, Russia.

In terms of the tectonic structure, the area is located in the northern part of the Ufimian arch within the eastern margin of the East European Platform, and in the Sylvian Basin within the Cis-Uralian foredeep. The broad distribution of the tectonic faults, which is clearly traced in aerial and satellite imagery, indicates the high tectonic activity of the research area. Several authors associate the appearance of fractures with the formation of the Ufimian anticlinorium structure. This process was followed by rejuvenation of the old fractures and the formation of the new ones in the Neogene and Quaternary periods. Undoubtedly, the intensive fracturing of the karstic rock mass favours the wide development of karst forms, both surface and underground.

Geological structure of the area is represented by 1) the Artinian and Kungurian carbonate and sulphate-carbonate-clay deposits of the Permian period Cisuralian series, 2) Neogene-Quaternary karst-slumping deposits, 3) Quaternary fluvial and alluvial formations — sandy loam, clays and loams with debris and rubbles of bedrock.

The results of more than 60-years of engineering geological research of the Quaternary overburden are the authors' maps of its lithological composition and thickness. The western part of Ust-Kishert village is not sufficiently explored with engineering geological wells, thus there is no conditioned data for this part of the study area [9].

Quaternary sediments represented by loam (2.89 km^2) occupy the most part of the study area (from the south-west to the north of the village). The central and northern parts are represented by clays (1.31 km^2). The smallest area is occupied by sediments represented by gravel (0.07 km^2) and located in the south-eastern part of the territory. To the west, there are bedrock exposures (0.27 km^2).

The maximum thickness of Quaternary deposits (more than 50 m) occurs in the north-eastern part of the study area. Small areas with a cover thickness of more than 40 m are encountered in the central and southwestern parts. Ust-Kishert village occupies the areas with a thickness of Quaternary deposits of 10–25 m (3.7 km^2) [9].

Most of the karst cavities (22 pcs, 39.3 %) were drilled in the areas with Quaternary deposits of 15–20 m in thickness. The maximum number of karst sinkholes (30 pcs, 30 %) is confined to the areas with a similar thickness of the Quaternary sediments (15–20 m) [9].

Underground and surface karst forms are found within the areas of the Quaternary sediments thickness of 10–25 m. 55 funnels were encountered on the surface and 20 karst cavities were found by drilling [9].

Karst cavities and crushed zones are reached by 60 and 24 wells, respectively. The karst cavities are registered while drilling mainly in the depth interval of 20–80 m. The total cavity thickness in the wells varies from 0.5 to 10 m. The exception is the northern part of the area where three cavities with a total thickness of 18 m were encountered in a single well. Crushed zones occur at the depths of 25–82 m. Their total thickness is 10–33 m and in rare cases the vertical size of the crushed zones does not exceed 10 m.

RESEARCH METHODOLOGY

The idea of using the anomalous values of overburden physical and mechanical properties as the indicators of the weakened rock mass elements location is implemented in this work. The intervals of the overburden anomalous strength parameters are determined by performing one-dimensional statistical analysis.

Only the Quaternary clayey subsoils were analysed in this work, because of the sufficient number of laboratory measurements of the strength properties for statistical analysis. Clayey subsoils used for analysis were of plastic to solid consistency. Subsoils with very high plasticity were not involved because of the sharp variation in strength parameters after water saturation of clay.

According to Terzaghi [11], the change in consistency (increase of water content) is accompanied by the three effects: 1) redistribution of water molecules and ions in adsorbed layers, 2) reorientation of clay particles and 3) breakdown of sedimentation and consolidation structure of clays. For example, for clayey subsoils of the plastic consistency, the angle of internal friction does not exceed 5–10 °. Tough and solid clays are characterized by the angles of internal friction of 14–35 °. The water saturation of sandy subsoils decreases the angle of internal friction by 1–2 °. The effect of water content on the shear resistance becomes particularly noticeable with the appearance of clay and silt fraction [7].

In addition, the interest to the properties of clayey subsoils is drawn by earlier researches carried out by the authors. Based on these researches, it was concluded that the most karst hazardous areas are those where loams with the thickness of 10–25 m are predominant. The largest number of karst cavities is found in the areas where loams have a thickness of 15–20 m (17 pcs, 48.6 %) and 25–30 m (11 pcs, 31.4 %). The areas composed of loams have the highest karst sinkholes occurrence (56 pcs, 72.8 %).

All the values of physical and mechanical properties of clays and loams retrieved from the wells were taken to perform a one-dimensional statistical analysis for obtaining the distribution curves of measured parameters. The most suitable theoretical distribution curves are applied to the empirical ones based on the corresponding distribution law (normal or lognormal).

In addition, we performed a one-dimensional statistical analysis only for the samples taken from wells in close proximity to those ones which revealed weakened rock mass elements.

The lack of data on the size of karst cavities and crushed zones, together with the absence of precise methodological recommendations on calculating the horizontal morphometric parameters of weakened rock mass elements from vertical ones, make it difficult to determine the maximum permissible distance for assigning a subsoil sample to the category of samples taken near the karst cavities. However, S.V. Shcherbakov and V.N. Kataev [10] found the relation between vertical and horizontal morphometric parameters of surface karst formations when studying the large volume of karst forms morphometry data. Using this relation and the maximum vertical thickness of the weakened rock mass elements of the study area, we can now determine their horizontal size. The sample taken within the distance of this size is now in the immediate vicinity of the weakened rock mass elements, in this case — 50–60 m.

The distribution curves of strength properties as a function of the presence of karst cavities were constructed after the one-dimensional statistical analysis. The differential curves that reflect the distribution of the physical and mechanical properties in the study area have the peaks that correspond to the average values of the investigated parameter that are the most common for the areas of the weakened rock mass elements. The range of mean values for the area is determined based on the mean M and the standard deviation σ from the mean and is equal to Mi ± σ.

Using the integral distribution curves of the strength properties of subsoils throughout the territory and on the sites close to the weakened rock mass elements we can find a certain coefficient k (1) which would represent the difference of the investigated parameters values (Figure 1):

$$k = \frac{X^A_{P_{0.1}}}{X^B_{P_{0.1}}}, (1)$$

where $X^A_{P_{0.1}}$ is the investigated parameter value near the weakened rock mass elements with probability of 0.1,

$X^B_{P_{0.1}}$ is the investigated parameter value on the entire study area with probability of 0.1.

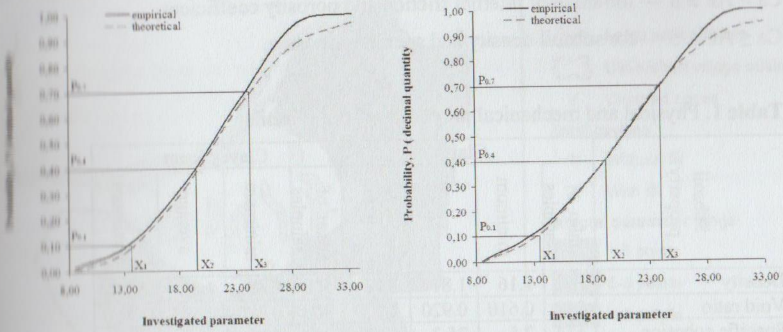

Figure 1. Integral distribution curves of the investigated parameter values. A — near the weakened rock mass elements, B — for the whole research area

Considering the values of investigated parameters for several probabilities (e.g. 0.1, 0.4, 0.7) we can find the average value of k, which can then be applied for similar by the natural structure territories on the basis of laboratory measurements of the overburden subsoil samples. In other words, it is possible to find areas of possible appearance of weakened rock mass elements calculating the strength properties by their distribution on the whole territory.

Apart from evaluating the strength properties of the overburden, we propose the obtaining an integral index of the overburden condition using the laboratory subsoil samples data — subsoil density ρ, subsoil void ratio e, specific adhesion c, and internal friction angle φ. The chosen parameters are necessarily obtained during the engineering geological and karstological surveys of the overburden. Current models of karst hazard assessments [1, 6, 8] used in engineering surveys account for the strength properties and density of overburden. Thus, data for the proposed analysis can be drawn from the engineering surveys conducted on site without any additional surveys. Subsoil water content *p*, which is also a necessary characteristic obtained in engineering surveys, is not considered in this work because of the constant variability and exposure to the anthropogenic impact.

The properties of the overburden subsoils were tested within the subrange (according to GOST 25100-2011. Soils. Classification) into lithological varieties division due to the resemblance of the average parameters values (Table 1). Complementary to clay and loam there are also sandy loam and sand and rubble subsoils in the overburden sediments. They were formed after the destruction of the bedrock carbonates, but were not used in the analysis because of the insufficient amount of laboratory data.

We performed the local analysis using statistical methods and computer modelling. According to the laboratory data, the order statistic is constructed for each factor. Then, the descriptive statistic was obtained — AF is the average factor value in the study area, and σ is the standard deviation. Further, the empirical and theoretical distribution curves were plotted in accordance with the law of random variable distribution determined earlier. The theoretical distribution curves indicate the intervals of background and anomalous values:

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$Ca \geq AF \pm \sigma$ — for angle of internal friction and porosity coefficient,

$Ca \leq AF \pm \sigma$ — for subsoil density and specific adhesion.

Table 1. Physical and mechanical properties of the subsoils

Subsoil property	Clay				Clayey loam			
	num. of samples	minimum	average	maximum	num. of samples	minimum	average	maximum
Density	252	1.16	1.81	2.03	508	1.48	1.82	2.11
Void ratio	252	0.610	0.920	2.700	508	0.370	0.863	2.160
Specific cohesion	114	2.5	25.3	52.0	244	0.8	19.4	65.0
Internal friction angle	101	6.0	19.0	31.0	192	3.0	21.1	37.0

The physical and mechanical parameters of samples were ranged by the intervals on the distribution curves and mapped using the sampling locations. The obtained maps then were graded by the level of karst hazard with the maximum of (3) assigned for anomalous parameter values and the minimum of (1) for background values. To detect the weakened karstic rock masses these maps were overlapped with each other. The result of the overlapping is an integrated cartographic model which has zones of the maximum total score values corresponding to the areas with the highest probability of karst cavities and crushed zones appearance.

Validation of the research was accomplished by a spatial analysis of the karst cavities locations proved by drilling in the study area. The results are presented in a form of a table and the number of underground karst forms spatially related to the categories of the integral model is noted.

RESEARCH RESULTS

The distribution curves of the overburden clayey subsoils strength properties are gained as the result of one-dimensional statistical analysis.

Using these integral curves, it is possible to find the average coefficients of transition from the background strength properties values to anomalous. For the angle of internal friction φ and the specific adhesion c, these coefficients are as follows:

1) $k\varphi0.1=1.07$, $k\varphi0.4=1.05$, $k\varphi0.1=1.03$, $k\varphi$ average=1.05,

2) $kc0.1=1.03$; $k\varphi0,4=1.02$; $k\varphi0.1=1,03$; $k\varphi$ average =1.03.

The analysis of physical and mechanical properties of the overburden resulted in an integral karstological model of the study area. The model was graded into three categories with different total scores (Figure 2). The territory with the average total score values has the greatest number of crushed zones and karst cavities. However, the highest density of karst forms is confined to the areas with the maximum total score values which corresponds to the joint locations of the zones of abnormally low or high values (Table 2).

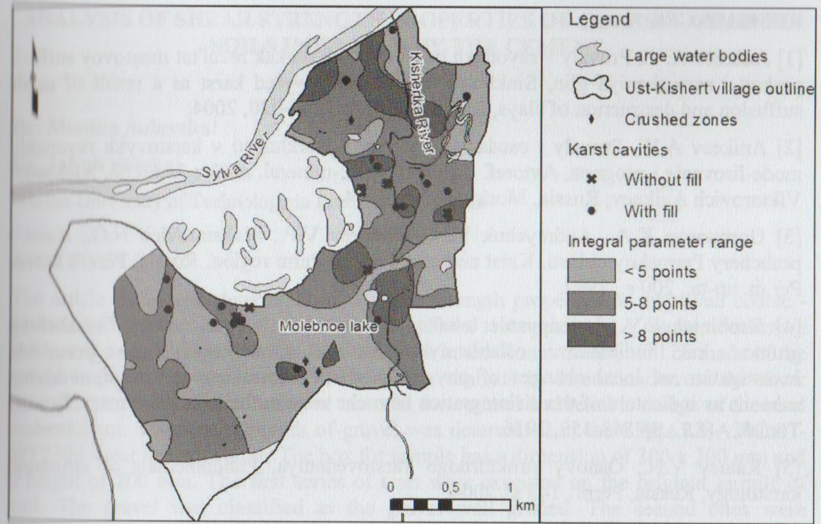

Figure 2. A map of the integral parameter for the overburden condition [4]

Table 2. Quantitative assessment of karst hazard according to selected categories

Hazard category	Integral parameter, points range	Area of the category (km^2)	Num. of karst forms		Density of karst forms (pcs/km^2)	
			crushed zones	cavities	crushed zones	cavities
1	< 5	2.30	4	10	1.7	4.4
2	5-8	2.40	14	34	5.8	14.1
3	>8	0.70	6	16	8.5	22.7

CONCLUSION

Assessment of the karst cavities and the crushed zones depth and morphometry within each category on the integrated indicator map was plotted on the graphs. The maximum vertical thickness of cavities is characteristic for the second category. It should be noted that the second category has 7 cavities that are not filled with sediments, the third one has 2 of the kind, and the cavities of the first category are all filled.

The obtained coefficients of kφ average and kc average can be applied for similar territories to determine the strength properties and approximate the abundance limits of the areas of possi-ble location of weakened rock mass elements.

The proposed technique of karst hazard assessment is based on the determination of the integral indicator of the overburden condition and has a local use and certain limitations. It makes possible to contour the possible areas of weakened rock mass, but not to specify the exact locations of karst cavities. However, through this analysis one can outline the direction of further detailed study.

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