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Modern approach to an assessment of karst hazard

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ABSTRACT: In article described a methodology to assess the karst hazard depending on the natural conditions of territories. Integral approach for realize the assessment is offered. Natural conditions are investigated through a set of separate factors. Hazard of karst process development is considered from a position of quantity and morphometry of anew generated karst forms. Analysis for revealing dependences between factors of natural conditions, quantity and morphometry of karst forms is carried out with application specially developed technique within a number of pilot areas of karst development located within the Permsky kray (Russia). As a result prognostic distributions and equations are received. The quantitative parameters, which allow estimating degree of karst hazard for each separate factor or a set of factors of natural conditions as a result of their integral accounting, are offered.

1 PROBLEMATICS OF KARST HAZARD ASSESSMENT

The problem of assessment of karst hazard at land development still belongs to the category of tasks which haven't received a final decision. Among all variety of the approaches any of them doesn't allow to specify unambiguously for sure a place, time and scale of karst activity. Complexity of studying and forecasting of karst can be explained by difficulty of its detection and need of the accounting of a large number of factors influencing the process.

Studying of experience of assessment of karst hazard, systematized from the position of separate indicators of karst activity on the one hand and an environment of development of a karst with another, and also their joint complex analysis (integral approach), allowed to create complete vision of considered problem. It is obvious the most complete in contents are those integral techniques of assessment of karst hazard that directed on comprehensive studying of karst process within observed part of the massif.

The modern approach to assessment of karst hazard has to correspond to the following principles:

1 consideration of the main natural conditions of karst development, expressed through a set of factors;
2 factors should be to provide highest success of the approach, has engineering-geological orientation and wide applicability in daily investigation practice;
3 it should be based on integral quantitative method with use of the probabilistic and statistical mathematical apparatus, allowing to carry out probability of generation of a new karst forms and also to establish their average morphometric parameters;
4 to be universal in respect to interpretation of final results independently of the territory and object of research.

2 FACTORS OF NATURAL CONDITIONS

The set of factors considered at assessment of karst hazard of territories, depends on character of a solving task, scale of researches and features of the mechanism and dynamics of karst development, and also on quality and the volume of the available data.

Many researchers carry out grouping the factors of natural conditions of karst areas by various criteria. Most often factors are grouping depending on their genetic similarity. Such principle of grouping is characteristic and meets in many adjacent geological sciences, and also in some other natural sciences (Sungatullin 2006).

In our opinion factors of natural conditions that apply in procedure of assessment of karst hazard, have to meet the following requirements:

1 easy to establish on materials of engineering investigation;
2 to be unambiguously interpreted independent to a method or equipment used for their determination;
3 to have a maximum universal character regardless of the research area;
4 to have a quantitative form of expression;

5 reflect the main conditions of karst development;
6 to be grouped depending on features of natural conditions of the karst massif;
7 amount of factors should not exceed 3–5 within a separate group, but in the same time so close as possible, reflect the character of the natural conditions, described by the group;
8 objectivity of assessment should not significantly go down when some factors are not included in the analysis; amount of excluded factors should not exceed 50% of its general number, but it can be factors that make up the whole group.

Our proposed list consists of 17 factors divided into 5 groups (Table 1). These factors are fully satisfied to conditions mentioned above. Most of them are widespread in the karst research practice (factors of geological, hydrogeological and engineering-geological groups). For example, thickness of different litho-stratigraphical complexes, levels of groundwater and their hydrochemical composition, expressed in integral form (mineralization), has repeatedly been used by many investigators (Fenk 1982, Lamoreaux & Newton 1986, Wilson 1995, Kaufmann & Quinif 2002).

It should be noted, current set of factors can be fully applicable for the territories and the whole region in general, investigated in this work. However, proposed set of factor with defined degree of accuracy can be applied for some karstological objects with similar conditions of karst development, which regionally localized worldwide.

Table 1. List of factors of natural conditions to integral assessment of karst hazard.

Factors	Character	Unit
Structural-tectonical factors:	***St***	
• Linear density of lineaments	L_l	km/km^2
• Amount of lineament intersections	M_l	pcs/km^2
• Lineament blockiness	B_l	km^2
• Distance from lineaments	R_l	m
Geological factors:	***G***	
• Thickness of cover deposits (depth of karst deposits)	m_p	m
• Thickness of Quaternary deposits	m_Q	m
• Thickness of Neogene-Quaternary collapse-karst deposits	m_{NQ}	m
Hydrogeologic factors:	***Hg***	
• Depth of groundwater static level	H_Q	m
• Depth of karst water static level	H_k	m
• Mineralization of groundwater	M	g/l
Geomorphological factors:	***Ge***	
• Slope of relief	B	°
• Excess above the average river water level	ΔH	m
• Distance from river net	U	m
• Slope of basin	$\tan\alpha$	
Engineering-geological factors:	***Eg***	
• Modulus of deformation of cover deposits	E_0	MPa
• Angel of internal friction of cover deposits	φ	°
• Coherence of cover deposits	c	kPa

3 KARST FORMS

Integral assessment of karst hazard should take into account both surface and underground karst forms.

Note that estimation of underground karstification in practice of geotechnical investigations still move to the background and often assessed by qualitative methods. In integral assessment of hazard among surface karst forms in analysis take a part sinkholes and depressions of collapse and piping-collapse genesis.

Analysis include investigation both old and modern sinkholes. For old sinkholes we do not know exact time of its formation. Modern sinkholes occurred during the period of monitoring for karst process.

In addition, the analysis involves primary and secondary collapsed sinkholes. As a result of primary collapse generates new sinkholes. Secondary collapses cause deepening and widening of existing sinkholes.

Underground karst forms involved in the analysis are presented by cavities and breaking zones established during borings. Breaking zones it is such sites in the body of karst massif presented by damaged and fractured rocks.

As the investigated characteristics of the karst forms serve their basic morphometric parameters. The basic studying parameters of the surface karst forms are diameters d and the depths z of sinkholes. Average values of diameters consider for a complex in the horizontal cross-section sinkholes. Studied morphometric parameters of underground karst forms are served heights and thicknesses of cavities and breaking zones, uncovered during drilling. Studied morphometric parameters of underground karst forms are heights h_p and thicknesses h_z of cavities and breaking zones, uncovered by drilling.

4 PILOT TERRITORIES

One of criterion mentioned above, which must correspond the integral technique of quantitative assessment of karst hazard, is universality that consists in able of its adaptation applicable to any karstic conditions independently of the study area. Succeed solution of such criteria is possible in a result of a complex analysis of natural conditions and karstification simultaneously within several reference areas, which localized in different environment. One of the first steps in this way can be study of karstic conditions and its comparison with factors of natural conditions of the massif within several territorial entities of the single chosen region. Similar idea was suggested by Andreychouk (1999). He express the opinion that revelation of regional relationships between karst collapse processes and ways of its expression can be used as auxiliary and in some cases as major criteria of stability estimation in karst areas.

As a pilot in this research were served karst massifs of Permsky kray (Russia), which localized within the town of Kungur, urban settlement of Polazna, settlement of Oktyabrsky and a site of pipeline route near the settlement of Krasny Yasil (Fig. 1). These territories located within the areas of development of carbonate-sulfate karst. Natural conditions of karstification at this site were active studied over the last 50–60 years. During this period accumulated extensive material, which was partially analyzed and systematized in the course of 5-year research program "Monitoring of karstic areas of Permsky krai" (2006–2010).

Figure 1. Permsky kray: location scheme of investigated territories.

5 STUDY OF ACTIVITY AND SCALES OF KARST PROCESS DEVELOPMENT

Estimation of impact of factors of natural conditions on the activity and scales of karstification can be obtained by the way of its comparison with karst forms and their morphometric parameters.

The general aim of comparison is determination of: 1) empirical and theoretical distributions of karst forms on the values of concerned factors; 2) distributions of morphometric parameters of karst forms and their relationships with studied factors of natural conditions. For these purposes uses methods of cartographical and graphical modeling and analytical interpretation of quantitative data.

5.1 *Indexing of variables*

For the purpose of diverse matching and comparing of results, studied factors of natural conditions and morphometric parameters of karst forms adduce to the general kind through their normalization. Procedure of normalization consists of dividing particular values of morphometric parameters y of every single karst form and factors x of natural conditions, which values fixed in the points of localization of this form, on their territorial maximums—the maximum values within the whole region. Thereby we obtain index scores I of the studied variables (Scherbakov & Kataev 2012, Scherbakov 2012):

$$Ix_i = \frac{x_i}{\max x}, \quad Iy_i = \frac{y_i}{\max y} \tag{1}$$

where Ix_i = index score of i-th value of factor; Iy_i = index score of i-th value of morphometric parameter.

The main advantage of indexation is the capability of comparison of different parameters with each other. Indexed scores of studied parameters have equal limits of variability—from 0 to 1. To obtain real values of the studied characteristics needs to execute inverse operation—multiply index scores on the territorial maximums typical for concerned factors or parameters.

5.2 *Karst process activity*

Assessment of karst process activity is establish through analysis of particular distributions of individual karst forms and their general distribution on values of factors of natural conditions. Analysis of empirical curves of general distributions allows selecting most approached theoretical distributions which characterized for current researched factor (Fig. 2). In analysis we are considering two basic theoretical distribution laws—normal and lognormal. In more detail procedure of analysis discussed in previously published papers (Scherbakov 2012).

Parameters of defined theoretical distributions (average values and standard deviations) of karst forms within studied areas are shown in Table 2. These parameters can be used to prognosis the karstification in areas of karst development where natural conditions of its evolution are similar with pilot territories, for which were defined theoretical distributions.

Assessment of probability of karst forms development by analysis of theoretical distributions consists in evaluation of integral function (cumulative distribution function), which determines relative frequency of karst forms occurrence within different intervals of values of studied factor.

As known, in mathematical statistics relative frequency often equates to probability of event appearance.

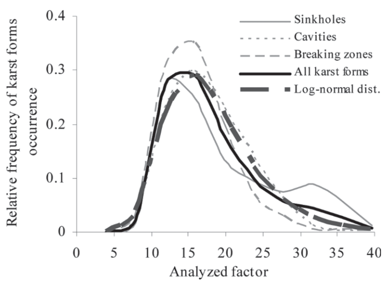

Figure 2. Example of distribution of karst forms on values of certain factor.

Table 2. Parameters of distributions of karst forms defined for different factors of natural conditions.

Factor	Max	Average*	Std dev*	Distribution law
L_l	14.7	–0.91	0.49	Log-normal
M_l	70.7	–2.23	1.26	Log-normal
B_l	2.9	–2.53	1.17	Log-normal
R_l	665.0	–2.12	1.09	Log-normal
m_p	80.7	–2.02	1.38	Log-normal
m_Q	36.6	–2.32	1.29	Log-normal
m_{NQ}	65.0	0.19	0.15	Normal
H_Q	19.6	–1.37	0.62	Log-normal
H_k	81.4	–1.39	0.96	Log-normal
M	21.2	–2.73	0.89	Log-normal
β	47.3	–3.57	0.98	Log-normal
ΔH	114.7	0.52	0.18	Normal
U	3028.7	–1.65	0.90	Log-normal
$tan\ \alpha$	2.22	–3.34	0.74	Log-normal
E_0	39.6	–0.98	0.37	Log-normal
φ	38.4	–0.62	0.26	Log-normal
c	58.5	0.38	0.15	Normal

*Parameters of theoretical distributions expressed in index form.

Thereby, probability of karst form occurrence can be estimated by integral function *F*, which for analyzed distributions defines as follows:

$$F = \frac{1}{\sigma_x \sqrt{2\pi}} \cdot \int_a^b e^{-\frac{(x_i - x_n)^2}{2\sigma_x^2}} \quad \text{– normal law} \tag{2}$$

$$F = \frac{1}{\sigma_{\ln x} \sqrt{2\pi}} \cdot \int_a^b e^{-\frac{(\ln x_i - \ln x_n)^2}{2\sigma_{\ln x}^2}} \quad \text{– log-normal law} \tag{3}$$

where σ = standard deviation of factor; x_n = average of factor; x_i = particular values of factor; *a*, *b* = limits of integration.

Estimations of probability defined with help of cumulative distribution function can be applied for investigation within some area where maximum *a* and minimum *b* values of analyzed factor are established. In this case as hazardous parameter assess an interval probability *Pab* of karst forms development. Accuracy of estimation with using interval probability *Pab* depends on the sizes of study area and homogeneity of natural conditions within its borders. Let's notice, such approach to assessment of probability is widely applies in reliability theory of systems.

To zoning territory by degree of hazard in case of lack of information the most proper to estimate the full interval probability *Pb* of karst forms development. Lower limit of integration *a* in calculation of *Pb* is equates to 0 and the upper limit *b* defines as value of analyzed factor of natural conditions in the observable point of the karst massif. Calculation formulas look as follows:

$$Pb = 2Fb \quad \text{– при } Fb \le 0,5 \tag{4}$$

$$Pb = 2(1 - Fb) \quad \text{– при } Fb > 0,5 \tag{5}$$

Parameter *Pb* varies within 0 to 1. Its application is useful in zoning not only specific limited area but in solving problems of comparison of karstic conditions and degree of karst hazard in various environments of karst development. Advantage of application full integral probability is in ability of its evaluation in every specific point of investigated territory (for example, with using factors defined in separately taken borehole) without binding with concrete territory or studying site. However need to take into account that parameter *Pb* is not a real probability value. It is just in some way reflects the activity and degree of hazard of karst development in considered environment.

5.3 *Scales of karstification*

Estimation of scales of karst development in geotechnical purposes is realized by means of analyzing of morphometric parameters of karst forms.

In the practice of karstological sciences is a known fact that distribution of diameters of sinkholes has log-normal character (Keqiang et al., 2010). Results of investigations of Gorbunova (1968) and Torsuev (2007) shown that log-normal distribution characterized for depths of sinkholes. Mass statistical analysis of morphometric parameters of sinkholes mapped within pilot territories of Permsky kray allowed identifying stable regression relationship between their average diameters and depths:

$$z = 0.3107d \tag{6}$$

Equation (6) recommends as prognostic not only within the territories of Permsky kray. With some precision its can be applied in other karst regions, which characterized by similar natural conditions of karst development.

In the result of statistical analysis of a large volume of information about morphometry of cavities and breaking zones, localized within Permsky kray, was defined a log-normal character of distribution inherent to them. Comparison of distributions of studying parameters of surface and underground karst forms revealed their actual coincidence (Fig. 3).

Generality of distributions and coincidence in development of underground and surface karst forms with close morphometric parameters within the same areas allows concluding about the close links between them.

Taking it into account becomes possible to forecast morphometric parameters of one karst forms on values of others (Fig. 4).

It should be noticed, that the dependence, shown on Fig. 4, is not universal. Its just describes the principal character of relation between sizes of surface and underground karst forms. However in nature are frequent events when fixes significant deviations from established dependence. It is usual predetermined by features of natural conditions of territory.

Forecast of morphometric parameters of karst forms depending on values of factors of natural conditions implements with usage of special developed method (Scherbakov 2012), which allows defining type and form of prognostic curves on the basis of established trend. Extract the information about existing trend allows operation of averaging values of morphometric parameters of karst forms in equals intervals of values of analyzed factors (Fig. 5).

Prognostic curves define analytically by selecting from general two-dimensional point cloud such of them, which maximally close to established trend (Fig. 6).

Coefficients of prognostic equations established within pilot territories are specified in Table 3.

Current equations allow implementing forecast of index scores of morphometric parameters of karst forms. The scopes of their applicability are not limited by investigated pilot territories and can be expanded to areas with similar natural conditions.

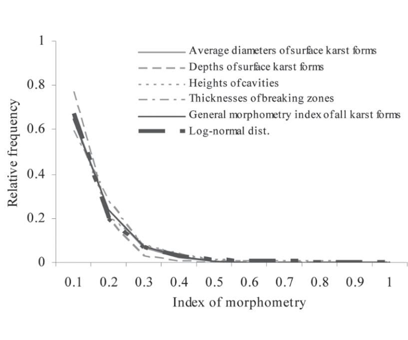

Figure 3. Differential curves of distributions of morphometric parameters of karst forms.

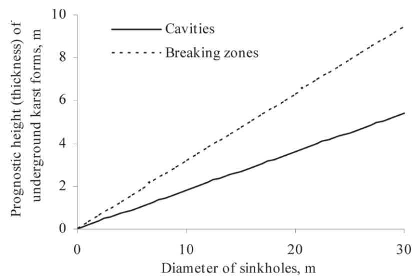

Figure 4. Relationship between morphometric parameters of karst forms.

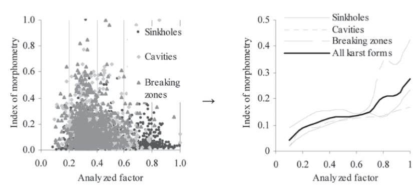

Figure 5. Algorithm of searching the relationships between morphometric parameters of karst forms and factors of natural conditions.

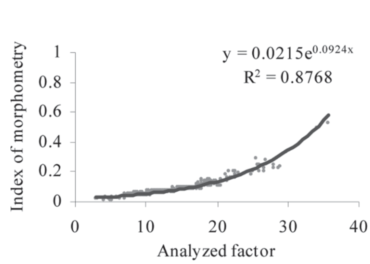

Figure 6. Example of prognostic curve.

Table 3. Coefficients and types of prognostic equations for estimation of index scores of morphometric parameters of karst forms.

Factor	Coefficients of prognostic equation		Type of dependence
	a	*b*	
L_l	0.5092	–0.3081	Exponential
M_l	0.2495	–0.6664	Power
B_l	0.0116	1.6450	Exponential
R_l	0.0003	0.0049	Linear
m_p	0.0049	0.0075	Linear
m_Q	0.0105	0.1080	Exponential
m_{NQ}	0.0099	0.0984	Exponential
H_Q	0.3162	–0.2667	Exponential
H_k	0.0056	0.0067	Linear
M	0.0384	0.8066	Power
β	0.4662	–0.8361	Power
ΔH	0.0059	0.0326	Exponential
U	0.0003	0.0000	Linear
$\tan \alpha$	0.0037	–1.2466	Power
E_0	0.0215	0.0924	Exponential
φ	0.0105	0.1144	Exponential
c	1.5155	–1.1148	Power

However, it is need to understood, that accuracy of prognosis will be higher in such cases, when degree of identity of natural conditions of karst development within the study area and pilot territories, which considered in presented researches, is maximum.

6 INTEGRAL MODEL OF KARST HAZARD

Probabilities assessments of karst hazard (*Pab*, *Pb*) and forecasting values of morphometric parameters in index expression *I* (hereinafter—parameters of hazard *X*) calculates for each factors of natural conditions. Integral estimation of these characteristics establishes from particular assessments, obtained for the single factors, which grouped depending on their genetic belonging. Mathematically integral model of karst hazard is written as follows:

$$X = a_{St}X_{St} + a_G X_G + a_{Hg}X_{Hg} + a_{Ge}X_{Ge} + a_{Eg}X_{Eg}, \quad (7)$$

where a = weighting coefficients; X = average value of hazard parameter in group.

Applying of weighting coefficients in integral model allows defining significance level of the particular assessments for each single group of factors.

It is correct in those cases, when distinct role in karst development within the studied area belongs to factors of defined groups or when factors in some groups were determined quite ambiguously.

Optimal solution of integral model, in the best way conforming to reality, is differs in every particular case. Searching of such solution consists in determination of weighting coefficients, which allows maximum objectively to define contribution of the factors of the every single group.

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