

REDUCTION OF RISK LEVEL AS ONE OF THE MAIN CHALLENGES OF DEVELOPMENT IN COVERED KARST REGIONS

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Abstract: The paper describes the experience of application of the residual karst risk concept, and presents coefficients of karst risk level reduction for planning constructional karst-protection. Practical experience of design for karstified territories of Nizhny Novgorod region demonstrates that special research of the interaction between constructions and foundations is required. Numerous accidents can serve vivid examples proving the need. In this situation it is important to approach the issue of safety in a proper way, taking into account probable economic, environmental and social damage. The problem can be solved by introduction of the karst risk level parameter, which permits to take into consideration constructional characteristics of objects (design philosophy, service life), as well as conditions and mechanisms of interaction between the foundation and the construction (sinkholes, local subsidence, karst-suffosion deformations, etc.). The importance of risk reduction is highlighted by current Russian Federal laws. Depending on karst risk level adequate karst-protection should be performed. For building projects, reduction of karst risk to a permissible level (conventionally equal to 1) is one of the most important research challenges of the karstified territories development, and its solution permits to plan appropriate karst protection measures.

Key words: karst, risk, sinkhole, structure, protection

Introduction

Development of a sinkhole on the ground surface is extremely difficult to predict. In order to be protected against such an unfavourable event, we need to have some criteria for appropriate engineering measures in line with the main principles of engineering development of karst-prone territories (Tolmachev, & Leonenko, 2011). Experience shows that various types of engineering protection performed in order to reduce karst risk level can have different efficiency. Nowadays we can identify the following main types of mission of antkarst protection activity (especially relating to covered karst regions):

- prevention of prohibitive extent of the geological environment pollution (1)

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- safety of the population and prevention of destruction of buildings and facilities (2)
- ensuring profitability of building projects and operation of facilities with due consideration of probable economic damage caused by karst deformations, cost of additional specific exploration including karst monitoring, antikarst protection, modification of operational conditions of constructions and insurance against karst risk (3).

Requirement of (1) and (2) should be understood as obligatory, while requirement (3) – as situational aspect of planning and implementation of antikarst protection programme. Antikarst activity can be performed before construction (I), during construction (II) and (or) during the service life of buildings or facilities (III).

We can also identify several main types of karst hazard (Tolmachev, & Leonenko, 2011):

- environmental impacts
- karst collapse
- underground karst deformations
- leakage in water storage basins.

The present article gives an example of karst risk assessment based on the notion of karst collapse hazard, which is related to sinkholes formed by collapses or karst-suffusion.

Sinkhole development in covered karst regions and induced catastrophic destruction

It is a well known fact that the regions of covered karst can be significantly affected by changes in the geological environment, causing a variety of karst manifestations (Sowers, 1996; Tolmachev, Troitsky, & Khomenko, 1986). Accordingly, a relevant approach is required to prediction of karst processes development (including deformations on the ground surface). Investigation showed that stochastic laws can be used to describe sinkhole development on a particular territory (Tolmachev, Troitsky, & Khomenko, 1986; Aderhold, 2005; Viktorov, 2006). It was demonstrated that sinkhole distribution conforms with the Poisson law, provided collapses are not interrelated and occur separately (Tolmachev, 1970).



Figure 1. Karst collapse ($d \approx 32$ m in diameter) in Dzerzhinsk “KhimMash”. Building without constructional antkarst protection (Russia), 1992.



Figure 2. Karst collapse ($d \approx 12$ m) in Dzerzhinsk. One more example of building without constructional antkarst protection (Russia), 1970.

It is necessary to consider conditions of sinkholes development, i.e. all factors which predetermine their dimensions and intensity. So far, the researchers have studied sinkholes with the diameter up to 40 m. Thus, mechanisms of large-scale sinkhole development $d \geq 40$ m (Figure 3) are still unknown and have to be studied in future. Engineering antkarst protection in cases of such a large-scale collapse seems impossible.



Figure 3. Karst collapse ($d \approx 60$ m) in Buturlino (Russia), causing destruction of two residential buildings and a granary in April, 2013.

Antikarst protection

Regulations adopted in the Russian Federation (Recommendations, 2012) include classification of antikarst protection types which is successfully used for practical purposes. The basic principles of the classification conform with the modern approaches to engineering protection declared in European codes.

Some of the antikarst protection types are listed below (with examples):

- hydrogeological protection (HG) – forced reduction of the underground water level
- geotechnical protection (GT) – use of geosynthetic materials
- karst-proof architectural planning of the structure on a certain territory (AP) – selection of the least hazardous karst area as a construction site
- constructional protection (CP) – reinforced design of the foundation and/or the frame of the building

- controlling and monitoring of structures and territories (CM) – use of warning equipment and signal indicators
- operational protection and maintenance (OM) – prevention of leakage into the ground from water pipelines, arrangement of rainwater drainage and technical water discharge systems.

As a rule, general approach to antkarst protection and types of activities are identified during engineering exploration at its early stage.

Considering a variety of technical procedures used in different types of antkarst protection methods, we can evaluate the versions and select the most efficient ones according to their engineering, geological and economic efficiency.

Methods of planning antkarst protection according to the karst risk level

Generally, in order to reduce prohibited level of karst risk to the acceptable value we have to plan a combination of antkarst protection measures. To do this the following problems need to be solved:

- demonstrate the appropriateness of the selected method for reduction of karst collapse risk
- develop an approach to evaluation of the coefficients influencing the reduction of karst collapse risk.

The current legislation and standards of the Russian Federation require assessment of risk induced by hazardous geological processes for the purposes of engineering and construction. Karst process is one of them. International practice includes some examples of successful karst risk assessment. Many of them were applied to assessment of karst hazard for the purposes of development in the underground areas in the regions of uncovered karst (Marinos, 2001; Filipponi, 2010). Examples of karst risk assessment for covered karst regions can be found in Russian publications (Tolmachev, Troitsky & Khomenko, 1986). The main contribution was made by a group of a few authors.

In Russia the following parameters are used to assess karst risk for practical engineering purposes:

- (1) P_{rb} - probability (risk) of damage to a particular construction caused by a sinkhole per a given period of time
- $P_{rb} = f(\lambda, A, T, d_{mid}, d_{max})$, where:
- (1.1) λ – intensity of sinkhole development (sinkhole/1ha*100years)
 - (1.2) d_{mid} - average sinkhole diameter
 - (1.3) d_{max} - maximal sinkhole diameter

- (1.4) A – area of the building or facility
- (1.5) T – predicted service life of the building or facility
- (1.6) the outlay of the foundation in plan view
- (2) R_n - acceptable specific karst risk of damage caused by a sinkhole to the area of 1ha per 100 years, and R_{nb} – acceptable karst risk of damage caused by a sinkhole to a particular building or facility per a given period of time, where:

$$R_{nb} = f(R_b, A, T)$$

The method of evaluation of the karst risk level for a particular building or land site is based on comparison between these two values. For practical engineering exploration and design purposes karst risk level can be described in the following way:

$LR_b = f(LR, A, T, \lambda, d_{max}, d_{mid}, \text{the outlay of the building or facility in plan view})$

$$LR_b = P_{rb} / R_{nb}$$

Depending on the obtained values of karst risk level a relevant capital or maintenance antkarst protection can be planned. Implementation of the antkarst protection programme results in reduction of P_r and (or) increase in R_n values. In order to reduce the level of karst risk for a building or facility LR_b a system of organizational, engineering and technological activities is needed. For every practical case appropriate protection activities must be specified by qualified specialists in various fields (expert judgment). The team of evaluators has to come to an agreement on a combination of measures which can reduce the value of LR_b to the acceptable risk value, i.e. $LR_b < 1$.

Practical application of the karst risk level reduction coefficient (LR) with the use of expert judgment

A team of Russian engineering karstologists coordinated by Ph.D., Prof. Tolmachev V.V. has developed an approach to selection of antkarst protection activities using the parameter of karst risk level (Table 1).

The proposed procedure is accepted and included into regional technical regulations in Nizhny Novgorod (Recommendations, 2012). In some case specialists in design and survey organizations interpret the procedure presented in the table as an accepted guide to action. In fact, the table only shows an example of planning antkarst protection programme. Consequently, we feel the need in validity verification of the selected antkarst protection activities aimed at reduction of karst risk level.

Table 1. A sample programme of cost effective activities on karst risk reduction according to specific karst risk level LR for territories with a specific geologic profile of Nizhny Novgorod region, Russia

LR	The most effective and economical type of antkarst protection measures aimed at reduction of karst risk level	Combination of measures depending on the karst risk level
< 0,1	None	
0,1-0,3	(A) Prevention of considerable anthropogenic impacts on the geological environment	A
0,3-1	(B) Refusal from isolated foundations of frame constructions	A+B
1-3	(C) Constructional antkarst protection of the foundations	A+B+C
3-10	(D) Continuous control of the condition of structures and foundations	A+B+C+D
10-30	(E) Improved rigidity of the upper building	A+B+C+D+E
30-100	(F) Special warning equipment and signal indicators	A+B+C+D+E+F
100-300	(G) Consolidation of karstified rock	A+B+C+D+E+F+G
>300	Construction is not recommended	

To begin with, we need to get constructional parameters of the building or facility requires for estimation of the karst risk level LR. We must also consider all types of probable damage caused by a sinkhole developed beneath the building or facility. The procedure is described in regulations (Recommendations, 2012). The method of specific karst risk R_n evaluation with account of probable environmental, economic and social types of damage conforms to the approaches of many European codes. From practice it is also known that the developers should perform independent assessment of acceptable risk on their own with the help of expert advisers in order to make correct decisions on antkarst protection.

It was found out that we can expect buildings and facilities to be affected by karst sinkholes to a different extent depending on their configuration. It was also noticed that separate parts of the same construction demonstrate different vulnerability, certain parts requiring additional attention. Alongside with the probability of sinkhole development, a relevant factor to consider in discussion on antkarst protection of the construction is its vulnerability. Consideration of vulnerability will permit to obtain protection parameters reflecting the risk of damage, as well as the probability of irreversible damage.

Comparison between P_{fb} and R_{nb} permits to get the initial karst risk level LR_{b1} . As a result of further data correlation, the value of karst risk level LR_{b2} after obligatory antkarst protection measures is specified within the limits 0 to 3. On achieving the level of karst risk required to ensure sustainability of construction $LR_{b3} < 1$, we can conclude that the selected antkarst protection measures have been efficient. Mathematically the situation can be expressed in the following way:

$$LR_{b2} = f(r_1 \cdot LR_{b1}) = f(\text{natural parameters}/r_{1i}; \text{structure parameters}/r_{1j})$$

$$LR_{b3} = f(r_2 \cdot LR_{b2}) = f(\text{natural parameters}/r_{2k}; \text{structure parameters}/r_{2m}),$$

where:

r_1, r_2 – coefficients of karst risk reduction, which influence on natural or structural parameters;

$(i, j, k, m) \in N, (N=1, 2, 3 \dots)$.

Obligatory antkarst protection measures guarantee prevention of anthropogenic factor of karst process development.

LR_{b2} – value of karst risk level which depends on the structural characteristics of the building, where: $i \in N, (N=1, 2, 3 \dots)$.

* - the parameters are estimated with the use of accepted geomechanical models of sinkhole development for particular geological and engineering conditions of the construction site being explored, as well as with the use of the results of expert assessment by a multidisciplinary team of specialists.

** - constructional antkarst protection is mandatory in such cases, as sinkhole development may lead to destruction (“KhimMash”, 1992, Figure 1).

*** - constructional antkarst protection is mandatory in such cases, as sinkhole development may lead to catastrophe (ecological catastrophe).

Table 2. The scheme of reduction coefficient r use for planning of the karst sinkhole protection programme in covered karst areas (a few territories in Nizhny Novgorod region, the Russian Federation)

Building/ structure/ foundation type	Natural parameters*		P_{rb}	R_n	LR_b (1)	Obligatory engineering protection	LR_b (2)	Situation- specific engineering protection	LR_b (3)
	(I),(II) - variants								
	d_{mid} (d_{max})	(I) λ (II) λ							
Public building/ reinforced concrete frame/ reinforced concrete strip		~0,06	~0,01	$5 \cdot 10^{-2}$	~1,5	OT	$\leq LR_{b2}$	-	< 1
	~15 (~30)	~0,8	~0,1	$5 \cdot 10^{-2}$	~20	CM+OT	$\leq LR_{b2}$	+CP (Figure 4)	< 1
Industrial building/ steel frame/ pedestal footing**		~0,005	$\sim 2 \cdot 10^{-3}$	10^{-3}	~6	CM+OT	$\leq LR_{b2}$	+CP	< 1
	20 (~40)	~0,1	~0,3	10^{-3}	>100	CP+CM +OT	$\leq LR_{b2}$	GT +(CP all structure) or (Figure 1)	< 1
Fuel reservoir/ steel shell/ concrete slab***		0,005	$\sim 2 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	~65	CP+CM +OT	$\leq LR_{b2}$	+CP	< 1
	~10 (~20)	0,5	$\sim 2 \cdot 10^{-3}$	$5 \cdot 10^{-4}$	>>100	CP+CM +OT	$\leq LR_{b2}$	AP (changing place of constructing) or (CP +GT)	< 1

In order to assess the extent of probable impact of a karst sinkhole we can apply the probabilistic method of prediction of the damage to constructions caused by sinkhole development (Tolmachev, Troitsky & Khomenko, 1986; Makhnatov & Utkin, 2012). The method takes into account maximal and average sinkhole diameters and permits to obtain a predicted karst sinkhole span. The span parameter is considered a relevant indication of vulnerability of the building or facility. When required, this parameter can be used as one of the components within the scope of all antakarst protection factors. However, evaluation of the constructional parameters of antakarst protection cannot be the only method of antakarst protection. The developers should also be aware of all other factors guaranteeing safety of the constructions (Figure 4 shows the photograph of a sinkhole under the building).



Figure 4. A case of efficient constructional antikarst protection (Russia). The building with a karst-proof foundation sustained a sinkhole $d \approx 6\text{m}$, (1970).

(a man in the photograph - Kopusov E.V.)

Conclusion

Risk assessment nowadays still remains a high priority and vital problem for the purposes of engineering and building on karst territories. The proposed algorithm permits to get verifiable quantitative criteria for selection of antkarst protection activities on the basis of stochastic laws of sinkhole development. The obtained coefficients for reduction of karst risk level enhance objective planning of antkarst protection in cases of karst collapse hazard.

For karst-proof engineering, construction and safe maintenance of buildings and facilities in karst-prone regions it is required to:

- develop a similar concept of karst risk level reduction for buildings and facilities of various functional and constructional types, such as linear constructions (e.g. railways, large-span bridges), etc.
- improve the methods of reduction of karst risk imposed on particular constructions by a range of probable karst deformations (local subsidence, settlement and other)
- develop computer programmes for karst hazard estimation for buildings and facilities at the design stage of construction on the basis of geoinformation systems with the use of the proposed procedure.

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