

KARST RISK ASSESSMENT FOR ENGINEERING IN NIZHNY NOVGOROD REGION, RUSSIA

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Abstract: Federal Standards of the Russian include the requirement of mandatory assessment of the risks induced by natural processes in order to make sure their values do not exceed acceptable limits. To meet the requirement a number of karst risk assessment methods have been developed for the regions of the country where the most significant hazard is presented by karst sinkholes. For this particular application karst risk is understood as specific probability of sinkhole development on a unit area per a unit time span with account of probable economic, social and environmental components of damage. The probability of sinkhole development is evaluated by specialists in engineering karstology and designers. They make use of the acceptable data on the environmental conditions and apply stochastic laws of sinkhole development in time and space, alongside with focusing on all other relevant specificity of the building or facility to be built. Acceptable limits of karst risks should be specified by a multidisciplinary team including designers, lawyers, economists, insurers, environmentalists, engineering karstologists and other specialists on the basis of their expert knowledge. It has been demonstrated that a ratio between predicted and acceptable karst risk values can serve a practically meaningful karst risk level indicator for the purposes of building on karst. This ratio can be used with a rather high degree of objectiveness to develop a programme of antikarst activities during both facilities construction and operation.

Key words: karst, risk, sinkhole, antikarst protection

Introduction

The problem of karst risk assessment is very important for Russia. In some regions karst presents the most serious danger, as compared with other natural processes. Karst prone territories in Russia are found in 90% of the regions of the country. Among the most hazardous regions there are Nizhny Novgorod, Tula, Perm, as well as Republics of Bashkortostan and Tatarstan. About 30% of the cities and towns in Russia experience considerable negative influence of karst processes. Industrial facilities and residential buildings in Moscow, Nizhny Novgorod, Dzerzhinsk, Kazan, Ufa, Tula, Berezhnyaky and some other cities, towns and settlements have been affected by karst causing damage or destruction.

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Karst-induced emergency situations have repeatedly taken place on the railways. Negative impacts of karst on safety of the railway traffic must be considered as one of the most important factors, especially for implementing programmes of high speed train service. Karst processes create a very specific problem for design, operation and termination of industrial and domestic waste disposal landfills and dumps. The main danger in this case lies in high probability of extensive and deep penetration of pollutants into the geological environment. To make matters worse, there are cases of unauthorized disposal of waste directly into sinkholes, thus causing problems of both environmental and legal character. Some bad accidents have also happened to operating main pipelines. This type of construction is specific, as accidents can be caused not as much by sinkholes as by subsidence.

A wide range of important problems arise in case of nuclear power plants (NPP) built on karst territories. Thus, karst hazard assessment for their major facilities is practically meaningless without due consideration of intense anthropogenic impact on the geological environment. Rigid requirements of national and international standards on design of NPP in karst territories to a great extent guarantee safety, and they correspond to a very low acceptable risk level. However, efforts to meet these requirements in practice lead to a number of problematic issues at all stages of the nuclear power plants service life, especially at the stages of the NPP site selection, engineering exploration and objective karst risk assessment. Erroneous engineering decisions made at these stages can have crucial effects.

The article presents some practical examples which demonstrate that karst risk assessment needs to be performed within the frame of an integral system “Karst process – engineering, economic and environmental activities”.

Concept of risk in Russian Federal laws

In the Federal law of the Russian Federation “On technical regulation” the concept of risk is understood as a probability of hazard to health and safety of the population and damage to property and the environment, with account of heaviness of all hazards and damage. This general definition of risk corresponds to the United Nations Organization concept of “Sustainable development” and is included into the “Urban planning Code of the Russian Federation”.

Bearing the above in mind, we can define karst risk as a probability of health hazard or threat to human life (social damage), damage to buildings, facilities and other property (economic damage) and to the environment (environmental damage) because of negative impacts of karst processes. Engineering activities

on karst territories can face several aspects of negative impacts of karst processes (karst hazard types), such as the following:

- Karst hazard, presented by probability of intense and deep penetration of contaminants into the geological environment (Hugnes, Memon, & LaMoreaux, 1994; Tolmachev, Maximova & Mamonova, 2005)
- Karst hazard presented by probability of inadmissible damage to or even destruction of constructions because of karst sinkhole development, local subsidence, settlements and other deformations (Tolmachev, Troitzky, & Khomenko, 1986; Reuter & Tolmachev, 1990; Aderhold, 2005)
- Karst hazard, presented by probability of complicated situations at the stages of construction and operation of underground facilities due to excessive karst water inflow (outburst) into the excavation area; local increase in overhead load to the underground facilities; complications with construction of deep foundations (Milanović, 2000; Marinos, 2001; Filipponi, 2010)
- Karst hazard, presented by probability of excessive water leakage from reservoirs (Likoshin, Molokov, & Parabuchev, 1992; Milanović, 2000)

Other aspects of karst hazard can be identified according to problems in various fields of economic activity in karst regions (such as water supply, mining, insurance, etc.). In certain situations integral assessment of karst hazard may become necessary, for instance, when national government needs to make decisions on joint development of a group of regions. In our opinion, formalized karst hazard assessment of this kind seems hardly possible; moreover, for engineering purposes it can appear to be counterproductive.

Some Federal laws of the Russian Federation, such as “Technical Regulations on safety of buildings and constructions” and “On protection of the environment”, include the requirements of obligatory evaluation of natural and natural/anthropogenic (ecological) risks to make sure their values do not exceed acceptable limits.

In order to fulfill the requirements of the legislation in design, engineering and exploration practice special scientific research must be done to evaluate each particular natural hazard with due attention to specificity of particular constructions. For this purpose a focused research programme is required, but so far it has not been developed. As is known by experience, at the stage of performing investigation we must answer the following questions:

- How to specify the time period for prediction of the risks introduced by hazardous natural processes with due consideration of the stages of construction service life and interests of the contemporary and future generations?
- How to specify acceptable risk?
- Can we adopt the content of “residual risk” and if we can, what kind of recommendations can be given to designers, engineers and explorers, real estate owners, insurance agents and other concerned parties?

Quite evidently, we should not expect to get easy answers to the above and many other questions in the nearest future, at least in Russia. To the best of our knowledge, though, the situation in other countries looks similar. The conclusion is based on the results of analysis of international publications on the problems of karst risk assessment in such countries as Germany, the United Kingdom, Spain, Croatia, the United States and China (Tolmachev, 2012). It may be useful and mutually beneficial to organize relevant international investigation of the territories characterized by hazardous exogenous processes with the focus on risk assessment for separate processes (karst, landslide, etc.). Alternatively, another approach can be followed and risk assessment should be performed individually for each particular hazardous natural process, region and type of construction (for instance, NPP, tunnels and railways among other). A method of assessing hazard of karst collapse in covered karst terrain widely used in Nizhny Novgorod region is described below.

Karst collapse risk

Karst collapse risk here is understood as a probability of karst sinkhole development on a certain area per a certain time span which may lead to economic (A), social (B) and/or environmental (C) loss. If we define the probability of sinkhole development in a unit area A (supposedly $A = 1$ ha) per a unit time span (supposedly 1 year or 100 years), we get a specific risk value (Pr). In most practical cases, for the purposes of civil engineering the unit time T is 100 years, because (according to Russian national building specifications) it conforms with the predicted service life for the majority of constructions. Pr values are obtained on the basis of investigation results, while probable approximate damage of various classes (A-B-C) should be assessed by a multidisciplinary team of experts (designers, environmentalists, economists, insurers, emergency management specialists, karstogists and some other).

It was shown earlier by a number of publications (Tolmachev, 1980; Raghy & Tiedeman, 1984) that sinkhole distribution in time and in space (under certain specified conditions) can be realistically described by the law of stochastic events (Poisson law). The distribution parameter is intensity ratio of sinkhole development λ (specific average number of sinkholes developed on the area of 1 ha per 100 years). Distribution of sinkhole diameters d on vast territories (with the area of several km²) is close to a lognormal type, and on small territories (with the area of several ha) it is close to a normal type (Tolmachev, Troitzky, & Khomenko, 1986). The distribution parameters enable objective assessment of average and maximal sinkhole diameter values (d_{mid} , d_{max}). Parameters λ , d_{mid} , d_{max} can be considered to be the most important results of the performed exploration. Additionally, investigation must obtain data on some particular relevant engineering and geological conditions as well as anthropogenic effects which may exert influence upon intensity of sinkhole development on the area where the construction is placed. The results of data procession allow the experts to specify coefficient K_1 in order to adjust the intensity ratio of sinkhole development.

Taking into account the above dependences, specific values of karst collapse risk Pr can be calculated by the following formulae:

$$Pr = [1 - \exp(-\lambda d)] \cdot V$$

$$\lambda d = \lambda K_1 K_2$$

$$K_2 = 1 + d_{mid} A_0 / [d_{max} (1 + A_0)]$$

where: \exp – exponent, A_0 – circumferential area (ha) around a 1 ha site at the distance of $d_{max}/2$; V – vulnerability of constructions built on 1 ha area of karst territory reflecting placement, design and other specific features of the entire constructional complex. Value V is expressed by a fraction of unit; it must be specified cooperatively by design, karstology and civil engineering experts.

In a similar way karst collapse risk Pr_b can be obtained for any separate construction with the area A_b and service life T_b :

$$Pr_b = [1 - \exp(-\lambda d \cdot A_b \cdot T_b)] \cdot V_b$$

where V_b – vulnerability of the construction at sinkhole development. Specific V_b value is assessed by civil engineers and karstologists with due consideration of design characteristics of the construction.

In this case coefficient K2 is described as:

$$K2b = 1 + d_{mid} A0 / [d_{max} (A_b + A0b)]$$

Acceptable karst risk

Engineering and constructional development of karst-prone territories entails a number of important issues to be considered: need in constructional protection measures, validity of protection design parameters, minimization of economic, environmental and social components of damage, need in insurance of the particular construction, check list for construction site selection, specification on the mode of operation of the construction exposed to karst risk, etc.

Solution to the related problems is simplified by comparison between karst risk (Pr or Prb) and the corresponding acceptable risk (Rn or Rnb). Acceptable risk is understood as acceptable probability of certain negative effects. In many practical cases specific values Pr and Rn are compared. Acceptable risk levels must be specified alongside with acceptable levels of economic damage (class A), social damage (class B) and environmental damage (class C). The approach described above guarantees conformity with the UNO concept of “Sustainable development of terrains”.

In design practice damage is often defined as loss caused by destruction of buildings or facilities by karst deformations. Economic loss is conventionally corresponded to the cost of the damaged building or constructions and other property, social loss – to probable loss of life or health hazard, environmental loss – to probable contamination of the environment.

Exact evaluation of these types of damage appears to be practically impossible. But it seems appropriate to classify probable damage and assess it by experts for particular most probable scenarios. As practice shows, damage caused in the process of engineering and constructional development of karst terrains can be grouped into three types according to classes A, B, C:

- (A) Economic damage: (I) low, (II) moderate, (III) high, (IV) extremely high
- (B) Social damage: (a) loss of life practically improbable, (b) probable loss of life - a small group of people, (c) probable loss of life – a large group of people, (d) – probable heavy loss of life
- (C) Environmental damage: (1) contamination of the environment is practically improbable, (2) probable local contamination of the environment, (3) probable massive contamination of the environment on the territory comparable with a small town area, (4) probable

massive contamination of the environment on the territory comparable with a region area

(Note: Some versions of quantitative characteristics of each damage type developed basing on the information gathered in the European regions of Russia are being verified at present (million roubles - in class A, number of victims – in class B, ha – in class C).

For practical purposes a matrix of specific Rn values has been developed which incorporates all defined types of damage. The matrix consists of 64 cells, showing corresponding values for a range of probable scenarios of destruction and damage caused by karst deformations. The present article does not include the entire matrix for technical reasons. However, two versions of the matrix were published: the full version (Tolmachev, 2010) and a simplified one for particular engineering problems (Tolmachev, 2007). Values of Rn in the adjacent cells (across and down) differ by half order of magnitude.

Values of Rn vary within a wide range depending on a scenario: from 0.1 (scenario AI-Ba-C1, for example, damage to a non-residential building of low importance) to 0.000005 (scenario AIV-Bd-C4, which approximately corresponds to acceptable probability of destruction of one of major NPP constructions). Table 1 shows a fragment of Rn value matrix for a fixed type of economic damage – AIV.

Table 1. Fragment of Rn value matrix for AIV

AIV				
B	C1	C2	C3	C4
Ba	0.005	0.001	0.0005	0.0001
Bb	0.001	0.0005	0.0001	0.00005
Bc	0.0005	0.0001	0.00005	0.00001
Bd	0.0001	0.00005	0.00001	0.000005

Comparison between Rn и Pr helps make inference about the level of karst risk on the investigated territory (with reference to various constructions and facilities) and, if necessary, plan antkarst protection activities of capital and maintenance character. For this practical purpose there is a convenient indicator of karst risk level expressed by the formula:

$$LR = Pr / Rn$$

Experience of practical use of karst risk parameters for engineering and exploration purposes

Example 1. Planning antkarst protection activities with the use of LR parameter for karst territories in Dzerzhinsk (Table 2).

Relevant engineering and geological factors and main design characteristic of buildings and facilities:

- karstified rock – limestone and gypsum
- depth of karstified rock - 50 – 70 m
- the overburden is composed of water-saturated sand and a 5 – 10 m thick clay layer
- major on-land karst manifestations – sinkholes ($d_{mid} = 12$ m)
- specific intensity ratio of sinkhole development $\lambda = 0.1$
- civil and industrial engineering
- moderate anthropogenic impacts on the environment
- shallow foundations

Table 2. Recommended programme of «antkarst protection activities»

LR	Antkarst protection activity to reduce LR value	Programme of activities
<0.1	None	
0.1 – 0.5	(a) Prevention of anthropogenic impacts on the geological environment	a
0.5 – 1	(b) Refusal from separate foundations in frame constructions	a + b
1 – 5	(c) Constructional antkarst protection of foundations or upper structures of the buildings from karst sinkhole impacts	a + b + c
5 - 10	(d) Continuous control of constructions, facilities and foundations of buildings	a + b + c + d

Example 2. Identification of acceptable karst risk values R_n for waste disposal landfills.

In Russia karst territories are grouped into five categories according to their potential sensitivity to pollution of the geological environment (Tolmachev, Maximova & Mamonova, 2005). It was proposed to specify acceptable risk levels R_n for landfills depending on the category and the class of contamination hazard, as shown by Table 3. Comparison between real specific risk of pollution of the geological environment at waste disposal landfills in karst lands and

corresponding specific risks helps plan a system of nature-conservation activities in order to prevent pollution of the geological environment.

Table 3. Values of Rn for landfills

Class of waste contamination hazard	Karst hazard categories of the geological environment pollution				
	I	II	III	IV	V
Low hazard	0.1	0.05	0.01	0.005	0.001
Moderate hazard	0.05	0.01	0.005	0.001	0.0005
High hazard	0.01	0.005	0.001	0.0005	0.0001
Extremely high hazard	0.005	0.001	0.0005	0.0001	0.00005

Some other typical examples of application of risk parameters for particular engineering problems

Zoning according to karst risk level LR was performed for a 30 km section of the highway railway Moscow – Nizhny Novgorod. Zoning was performed separately for two situations: (1) normal speed train operation and (2) high speed train operation. As a result, recommendations were given to impose speed limits for train operation at certain sections of the rail track characterized by high levels of karst hazard and to plan a number of maintenance activities of in order to reduce LR values.

A construction site for major blocks of nuclear power plant project was chosen with specific karst risk value below the acceptable level ($Pr_b < Rn_b$). According to Russian standards, $Rn_b = 10^{-7}$ per year.

An improved version of the method for design parameter of constructional antikarst protection of buildings and facilities from sinkholes (“determined sinkhole span”) has been developed on the basis of Pr and LR estimation (Tolmachev, Troitzky, & Khomenko, 1986; Makhnatov & Utkin, 2012). The method described above has been tried in dozens of projects in Nizhny Novgorod region.

Conclusions

Risk assessment for the purposes of building on karst territories and use of the concept of risk in engineering and environment protection activities make it possible to minimize inevitable loss.

Karst risk assessment must be performed with an allowance for various aspects (types) of karst hazard.

Comparing the predicted karst risk value with its acceptable value reflecting the probability of certain loss and damage of various types complies with the concept of «Sustainable development of terrains» based on integrated approach equally focusing on economic, social and nature-conservative components.

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