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Karst hazard assessment in the design of a residential complex in Moscow

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Abstract. The composition and content of necessary engineering-geological research providing accident-free operation of buildings and constructions in karst areas are considered. These studies include karst hazard assessment and rational selection of karst protection measures. The results of the prognostic assessment of karst sinkhole formation possibility on the territory of about 4 hectares, allocated for construction of the first stage of the complex of residential buildings of different numbers of floors in the northwest of Moscow, are presented. The basis was the results of site investigations, during which, in particular, several dozen boreholes were drilled to uncover soluble rocks. Karst hazard assessment included an in-depth analysis of engineering-geological conditions of the future construction site and adjacent territories and took into account the possibility of the occurrence of karst sinkholes of different genetic types in this city area. When building forecasts and karst risk assessment, calculated methods of probabilistic and deterministic character were used, allowing to determine the necessary conditions and parameters of karst sinkhole formation in quantitative terms. The results of the karst hazard assessment were considered when selecting karst protection methods.
Keywords: karst, sinkhole, hazard, risk, prognosis, anti-karst protection

1 Introduction

Currently, all over the world, the safety of the construction of buildings and structures erected in karst areas is achieved through the application of various engineering protection measures [1], among which a unique role is played by protective measures of structural and (or) geotechnical nature [2]. All this should be provided for at the stage of construction project design, and the basis for rational choice of karst protection methods is the information obtained during site investigations (mainly geological) on the territory of future construction. However, this information may only sometimes be used directly for this purpose.

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The point is that for designing karst protection measures (first of all, structural and geotechnical), it is necessary to know some parameters characterizing karst hazards for specific objects. Actually, quantitative assessment of karst hazard is a procedure for determining these characteristics by means of special analytical processing of site investigation data [3]. Three circumstances are assessed: a) the presence of existing karst manifestations on the territory of future construction, b) the possibility of changing their condition, and c) the possibility of forming new karst manifestations. This considers the technical parameters of the projected object and the nature of its negative interaction with karst manifestations, which may manifest itself in the form of a) difficulties in the construction of foundations and tunneling; b) increased filtration losses from artificial reservoirs; c) the possibility of subsidence or sinkhole under the foundation of a building or structure. Generally, karst hazard assessment is predictive.

For residential buildings and industrial enterprises erected in karst areas, the main danger is from sinkholes [4] and, therefore, the primary evaluation parameters required for karst protection design are the probability of karst sinkhole formation under the building foundation and its diameter [5]. In our country, there is a practice of some universal approach to the assessment of the danger of karst sinkholes and subsidence for industrial and civil construction objects based on the analysis of data obtained during geological surveys [6]. In some cases, this practice yields good results, but some situations require non-standard solutions in the choice of evaluation criteria, which is especially characteristic of urban areas. Consider one such case.

2 Materials and methods

The high-rise urban development complex is to be built in the Northern Administrative District of Moscow. The first stage involves the construction of two blocks of the complex on an area of about 4 hectares, including buildings of different numbers of floors, of which the tallest building, located in the first quarter, should have 46 floors (Figure 1). Residential buildings are characterized as structures of increased and normal levels of responsibility. Their planned lifespan is 100 years. The necessity of karst hazard and karst risk assessment at the construction site of the residential complex is stipulated by the currently valid, both in the city and in the country, instructional and normative regulations. Additionally, this need is enhanced by the fact that approximately 500 m to the northeast of the site is the boundary of the area qualified as dangerous in terms of the possibility of sinkholes [7]. At the end of the last century, there was a rather intensive karst formation within its boundaries, accompanied by the destruction of three residential buildings.

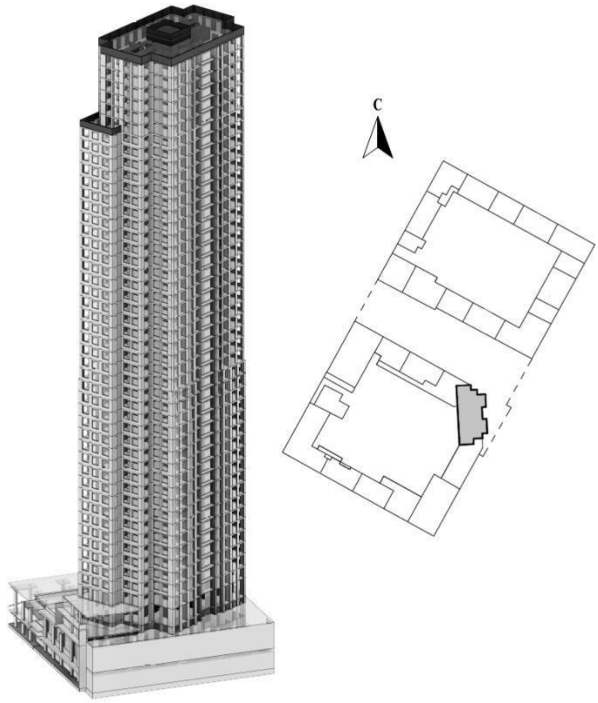

Fig. 1. Structural solution of the tallest building of the first stage of the projected residential complex (view from the southeast). On the site plan of blocks 1 and 2 to the right, the building is highlighted in gray.

Up to a depth of 80 m in the geological section of the future construction site of the first two blocks of the residential complex, the dominant sediments are Carboniferous and Jurassic, represented by carbonate rocks and clays. Above this depth, there is a relatively thick cover of Quaternary sediments, mainly composed of glacial, water-glacial, and river formations in the form of sandy and clayey soils. Hydrogeological conditions of the territory up to the same depth are characterized by the presence in the rock strata (from top to bottom) of a) unconfined Quaternary (supra-moraine) aquifer; b) confined and unconfined supra-Jurassic-Upper Carboniferous aquifer complex; c) confined Upper Carboniferous aquifer; d) confined Upper-Middle Carboniferous aquifer complex. The structure of the rock strata within the built-up area is characterized by noticeable spatial variability and heterogeneity (as can be seen in Figure 2), which is primarily determined by the presence of buried erosion valleys of different geological ages.

Soluble rocks, which include Carboniferous limestones, are weakly fractured. During drilling operations, virtually no voids and caverns open and filled with redeposited material were found in them. No surface karst manifestations confirmed by site investigations were observed both on the site and at some distance from it. Nevertheless, it was decided to protect the residential complex as much as possible from the negative consequences of a karst sinkhole formation under the foundations of any of the buildings if such an event does occur.

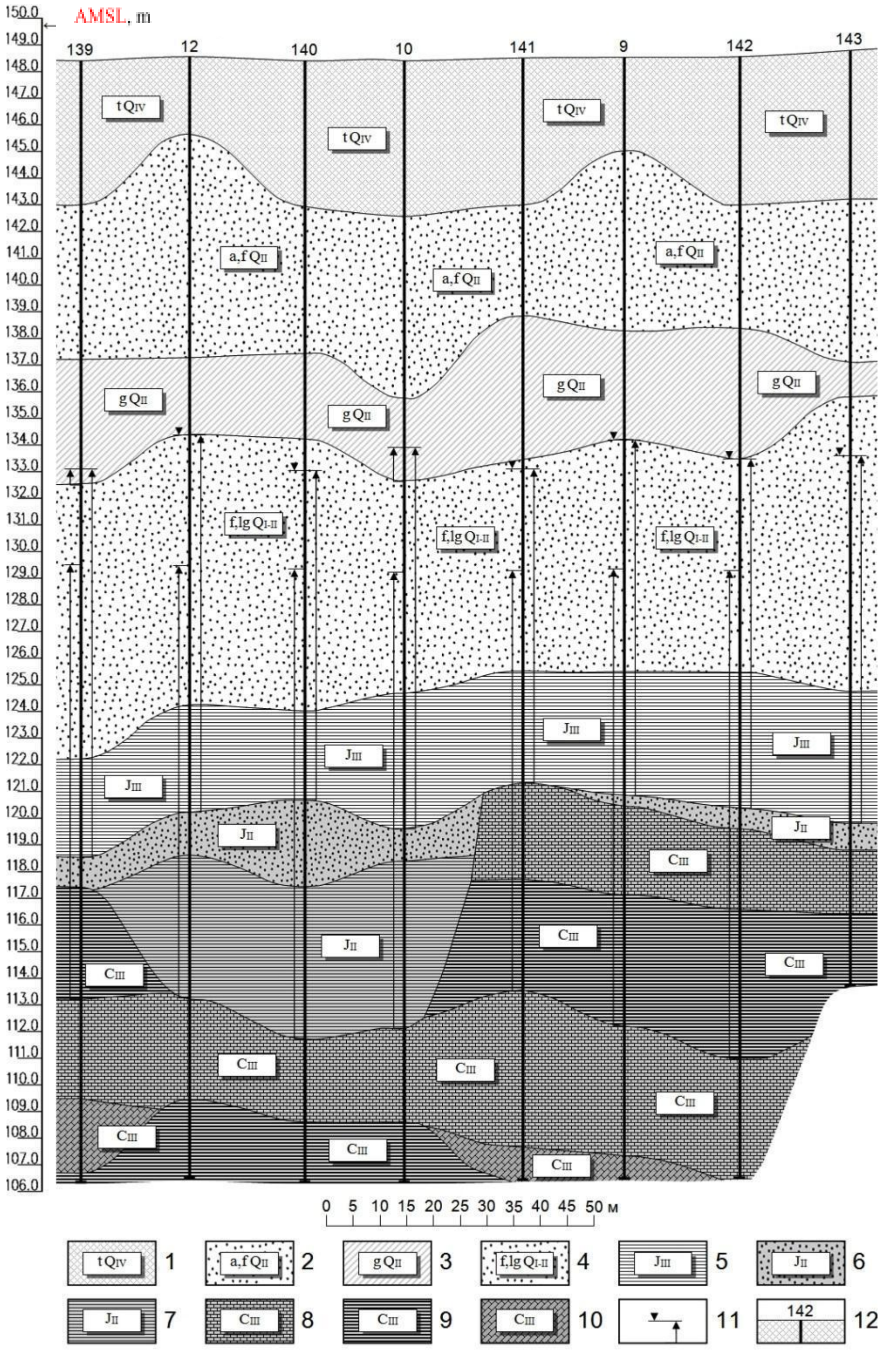

Fig. 2. Simplified geological section of the site of blocks 1 and 2 of the projected residential complex (the section line is shown in Figure 3). 1 – man-made soils (mainly sands); 2 – Middle Quaternary alluvial-fluvioglacial sands; 3 – Middle Quaternary moraine (loams); 4 – Lower-Middle Quaternary fluvioglacial sands; 5 – Upper Jurassic clays; 6 – Middle Jurassic sands; 7 – Middle Jurassic clays; 8 – Upper Carboniferous limestones; 9 – Upper Carboniferous clays; 10 – Upper Carboniferous marl; 11 – free (left) and piezometric (right) groundwater levels; 12 – borehole and its number.

3 Results

When assessing the karst hazard on the site of future construction of the first and second blocks of the residential complex as the initial information were used the results of site investigations performed in 2022, archival materials of other survey organizations, as well as information set out in the special literature. The assessment had a quantitative character and contained a forecast of the possibility of karst sinkhole formation under the foundation of any of the designed buildings during its service life and recommendations on the choice of anti-karst protection measures considered the level of karst risk for the designed object within the natural-technical (namely, litho-technical [8]) system "geological environment-building". The studies required to perform the karst hazard assessment were carried out in several stages.

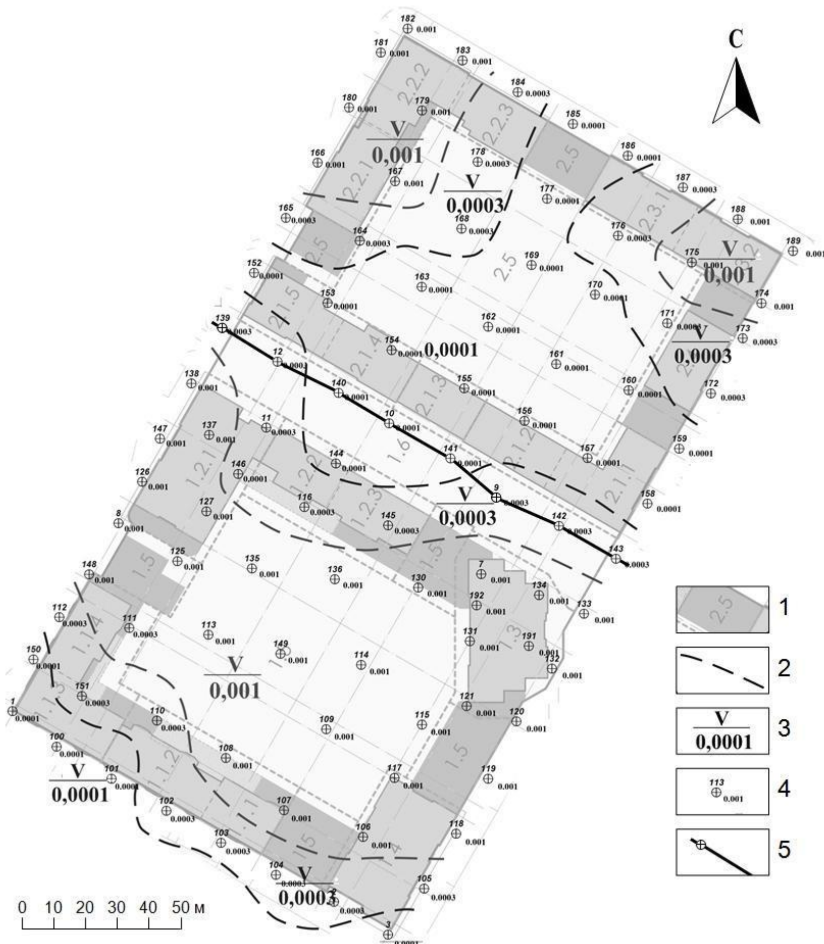

Fig. 3. Site zoning scheme of blocks 1 and 2 of the projected residential complex on the intensity of sinkhole formation. 1 – contours of buildings and their numbers; 2 – boundary between the territories with different intensity of sinkhole formation; 3 – assessment of the territory: karst hazard category in the numerator, sinkhole formation intensity in the denominator (number of sinkholes formed during the year in the area of 1 km^2); 4 – borehole, its number and the corresponding value of sinkhole formation intensity; 5 – geological section line (see Figure 2).

In the first stage, the existing engineering-geological situation at the projected construction site and neighboring territories and its changes over time were comprehensively analyzed. The history of the formation of surface karst manifestations in the northwest of Moscow was considered [9]. As a result, zoning of the construction site of the first and second blocks of the projected residential complex was performed according to the intensity of the expected sinkhole formation (Figure 4). It was concluded that three genetic varieties of karst sinkholes could be formed at the site [10]: collapse sinkholes, liquefaction-collapse sinkholes, and phreatic piping-collapse sinkholes.

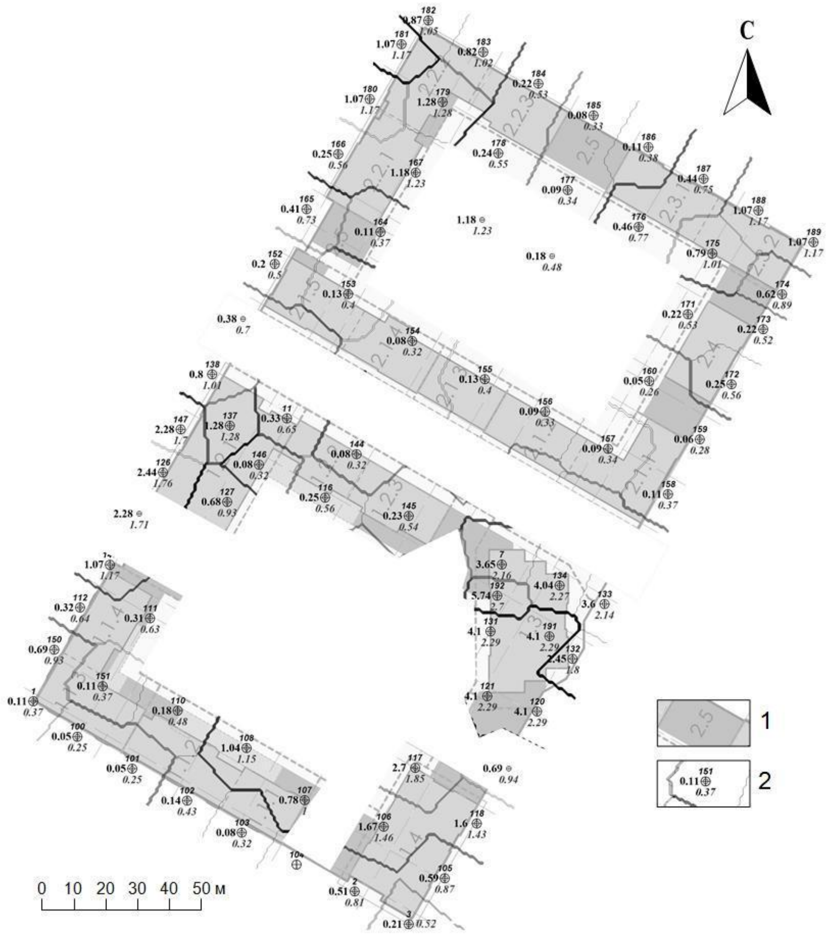

Fig. 4. Site zoning scheme of blocks 1 and 2 of the projected residential complex on the parameters of structural karst protection for buildings of increased level of responsibility. 1 – contours of buildings and their numbers; 2 – borehole, its number and expressed in decimal fractions corresponding values of the calculated area of weakening of sinkhole (direct font) and its equivalent design diameter (italics). The broken lines show the boundaries of the zoning domains.

The second stage of karst hazard assessment included prognostic calculations based on geomechanical models. First, the diameters of collapse sinkholes in case of their occurrence under the foundations of the designed buildings were calculated. The calculations were carried out according to the methods of G.M. Shakhunyants [11] and V.M. Kutepov [12], and a comparison of the results of these calculations showed their satisfactory convergence. Then, according to the method of A.V. Anikeev [13], the possibility of the formation of breaches in the clay layers overlapping the first limestone layer from the surface was evaluated. After that, according to the methods of V. P. Khomenko, the principal possibility of formation of liquefaction-collapse sinkholes [14] and phreatic piping-collapse sinkholes [15] was evaluated. Predictive calculations were performed for points corresponding to the location of each of the boreholes that penetrated the soluble rocks. According them sinkhole diameters must be in diapason from 6.5 to 19.4 m.

During the third stage, the risk for the designed residential buildings from possible formation of karst sinkholes under their foundations was assessed, which, in accordance with the Russian Federal Law No. 184-FZ "On Technical Regulation," is understood as "the probability of causing harm to the life and health of citizens, property and the environment, taking into account the severity of this harm". Thus, karst risk assessment (as an element of karst hazard assessment) had a probabilistic character and was carried out in accordance with the prescriptions of methodological documents developed in the 1980s by specialists of two leading research institutes of the USSR Gosstroy [5, 16]. In Russia, these methods have been successfully applied in engineering surveys and design up to the present time. The result of the third stage of research was the zoning of the construction site of the first two blocks of the projected residential complex by two parameters characterizing the possible negative impact of sinkholes on buildings (Figure 5), which can be neutralized by protective measures.

In the end, the design organization received the necessary information for specific choice of anti-karst protection methods and calculation of its parameters for each building considering the proposed a priori structural and geotechnical solutions (Figure 5). In addition, preventive, protective measures of construction-technological and operational-monitoring nature were recommended to reduce the karst risk to negligible. They should be performed at all stages of the life cycle of the designed structure.

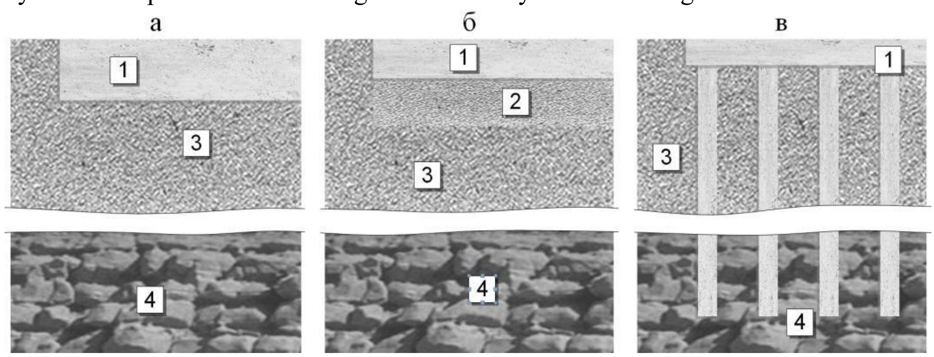

Fig. 5. Simplified scheme illustrating possible constructive and geotechnical solutions adopted in the design of buildings of the first stage of construction of the residential complex: a) monolithic slab foundation; b) monolithic foundation slab with base reinforcement; c) pile foundation. 1 – reinforced concrete structures; 2 – grouted soil; 3 – Quaternary sands; 4 – Upper Carboniferous carbonate rocks and clays.

4 Discussion

In the course of karst hazard prognostic assessment on the site of the first two blocks of the projected residential complex, the principle of reasonable sufficiency was applied, and processes or factors that do not have a significant impact on the possible formation of sinkholes under the foundations of buildings were not considered. First of all, it concerns the estimation of cavity growth rate in soluble rocks (i.e., their dissolution rate), which has recently been persistently cultivated as a necessary element of karst hazard assessment [17]. This criterion has not been evaluated for two reasons: firstly, it is meaningless in relation to limestones that have very low dissolution rates, and secondly, such an evaluation can only be correctly carried out experimentally in the field [18] or laboratory [19], which in these circumstances is difficult and time-consuming.

The main focus of karst hazard assessment was on geologic processes, which, according to V.V. Tolmachev et al. [4], are included in the concept of “karst”, but occur not in soluble rocks but in soil cover. These destructive processes include gravitational collapse, piping, liquefaction of water-saturated sands, and some others. These processes directly form sinkholes in areas of covered karst, where soils overlaps soluble rocks, and it is on the territory of this type and Moscow.

The second principle underlying the methodology of the predictive karst hazard assessment for the buildings of the first phase of construction of the projected residential complex was that the assessment had both a probabilistic and deterministic character. Finally, each of the domains identified as a result of the study site zoning acquired its values of two indicators affecting the technical parameters of anti-karst protection measures: the calculated area of sinkhole weakening and its equivalent calculated diameter (Figure 4). Often, for these purposes, they stick to calculations of sinkhole formation intensity and average diameter of sinkhole [6], and when it is impossible, satisfied with the value of the diameter of the expected sinkhole, obtained by deterministic methods [17].

5 Conclusion

Conditions for karst development at the construction site of the first two blocks of the projected residential complex are assessed as unfavorable. The formation of a sinkhole under the foundation of any of the residential buildings over its design life is improbable. Nevertheless, the investigated site should be considered as potentially dangerous from the point of view of the possibility of its realization, additionally considering the fact that for the territory of such a large and intensively developing city as Moscow, the occurrence in the future of unforeseen anthropogenic impacts on the geological environment and, especially, on the underground hydrosphere cannot be excluded. To ensure total safety of the projected buildings and structures of the residential complex in the conditions of the existing (even if low) karst risk, it is necessary to take protective measures of structural and (or) geotechnical nature, as well as a number of preventive measures implemented during the object operation.

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