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Geological structural criteria of karst assessment in urbanized territories

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ABSTRACT: Geologic environmental condition issues within the limits of the urbanized territories located in areas of karst rock development are of particular importance. The characteristic feature of these territories is the development of hazardous, dynamically developing deformation phenomena (chasm) in the bases of buildings and constructions that leads to taking engineering objects out of service. While practicing prediction of karst there are often situations when it is necessary to give a substantiation of stability of the limited area. Similar situations are typical in cases of additional development of active industrial zones or urban building plots. For non-karst professionals all territory of the site appears to be hazardous and inadaptable for development. In its turn, for karst experts the difficulty of solving the problem is in territory limitations. Here are presented almost identical structural-geological and hydrogeological conditions, the relief is changed, karstic rock exposure is absent. This demands application of non-traditional approaches to karst analysis. The analysis of geologic structure features of the territory, expressed quantitatively, and its further spatial comparison to units with karstic forms development allows carrying out quantitative and qualitative prediction of karst with a high degree of confidence.

1 INTRODUCTION

Steady tendency of increasing losses due to dangerous natural and industrial processes including karst raise a topical issue of necessity to develop novel methods of public safety control based on preliminary identification, forecasting, risk analysis.

The quantitative basis for prediction of karst is formed by specific database, while the cartographical basis of estimative and prognostic schemes is a map demonstrating actual material of engineering-geological activities being conducted with a territorial binding of karst formation. It has to be accompanied by geological-lithological cuts, data of layer-by-layer documentation of deposits and rocks, exposed while drilling or sinking a shaft. Using the following phenomena as karst vulnerability indicators a researcher has an opportunity to analyse and compare within the karst units: 1) heterogeneity of lithological structure of the deposits blocking karstic rocks, 2) its water permeability and 3) unequal capacities, 4) structural-textural heterogeneity of karstic rocks (by lateral and depth of bedding), 5) elements of a relief of a karstic rocks roof, 6) elements of a land relief, 7) spatial compliance of the attributes listed or their constellation to location of surface and subsurface karst forms.

The criteria of prediction of karst listed above as well as some other form the basis of karst monitoring system developed for Perm Krai territory (Western Urals, Russia) [2]. The basic functional elements of karst monitoring system are shown in Figure 1.

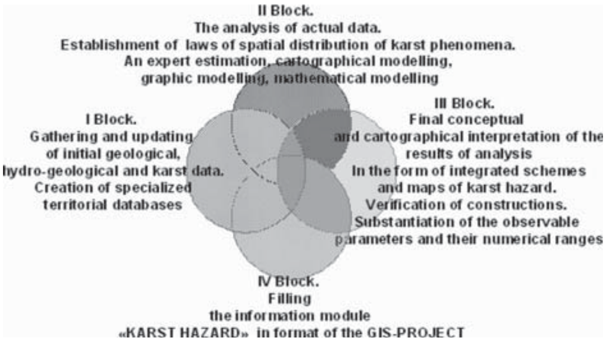

Figure 1. Basic functional elements of karst monitoring system.

As an example we will give the main principles of adaptation of geological criteria for a karst hazard assessment in the territory of Kungur city—the classical area of development of a sulfate-carbonate karst in the Western Urals.

2 GEOLOGICAL STRUCTURE

The upper part of a sedimentary cover is formed by the rocks of the Perm, the Neogene and the Quaternary systems. The Perm system is presented by deposits of artinsky and Kungur layers. Deposits of the Kungur layer are presented by the rocks of fi-lippovsky and irensky horizons.

The filippovsky horizon (P_1k^{ph}) is widespread almost on all territory of the city, but on a surface emerges only in its eastern part. The horizon comprises dolomite and dolomitic limestones mostly. Capacity of rocks fluctuates from 50 to 80 m. The irensky horizon (P_1k^{ir}) within the city boundaries and its suburbs is presented by fragmentary intersection of sulphatic and carbonate assizes.

The Neogene (N) is presented by a karstic breccia and landslide karstic deposits. Capacity of deposits is unsteady and can swing at short distances.

The Quarternary system (Q) is mainly presented by alluvial and deluvial loamy, argillo-arenaceous, and sand-and-gravel and chisley deposits which capacity fluctuates from 4–5 to 40 m.

3 HYDROGEOLOGICAL CONDITIONS

In the studied territory underground waters are confined to quarternary alluvial sand-and-gravel and loamy deposits, irensky carbonate and sulfate and artinsko-filippovsky carbonate formations of the Perm age. The territory is characterized by a complex nature of distribution of underground waters and their complex hydrochemistry. The most significant role in formation of regularities of development and distribution of surface and subsurface karst occurrence is played by spatial features of a bedding, dynamics and chemistry of underground waters of the irensky water-bearing horizon. Water cut of rocks of the irensky horizon has a sporadic character. The isolated underground waterways are typical for the horizon. Abundance of water of rocks of the horizon is various, water constitution is mainly sulfate-calcium with a background mineralization to 3,0 g/dm3. In the hydrodynamic relation waters are mainly related to two zones: vertical and horizontal circulation.

4 ATTRIBUTES OF A SPATIAL RATIO OF DISJUNCTIVE TECTONICS TO KARSTIC FORM ELEMENTS

Activity of karst processes, their directivity is caused mainly by dynamism and aggression of surface and subsurface waters controlled in time and space by structural factors, which form particular conditions for these waters circulation.

Structural-tectonic features of the territory form a primary karstogenetic background, a framework on which "external", more dynamic in their development processes of natural or natural and technogenic karst modeling are applied.

Ascertainment of a spatial ratio degree of fractured tectonics and karst occurrence is an important criterion in prediction of karst.

Detecting structural regularities of the massif episurface with their relation to karstic phenomena appears to be a difficult, laborious and not always effective process. However, such regularities and relations, though in the hidden form, exist in nature. Their establishment facilitates the solution of theoretical and practical tasks of the karst forecast to great extent [1, 3]. Figure 2, 3 demonstrate examples of spatial ratio analysis of assumed tectonic damages zones, traced by lineaments, and karst forms, conducted within Kungur territory (Western Urals, Russia).

It should be noted that in karstic massifs zones with high density of systemic fissures, breakage zones, faults, etc. are more dynamic in tectonic and, as a result, in hydrogeological and hydrochemical relation.

Ultimately the researcher can draw up final prognostic equations, using the revealed regularities of a spatial ratio of disjunctive tectonics elements and karst forms (Tab. 1).

Practice of karst researches shows that among many spatial regularities of karst occurrence the distribution of its forms depends often on orientation of tectonic and neotectonic fissures, breakage zones location, explosive damages, and places where fissures, faults or breakage zones intersect are the potential for creating conditions of cavities formation.

Considering one of conditions of karst development, namely the permeability degree of karstic and blocking deposits, the structural-tectonic criterion should be put and considered among the main.

At the same time, it is necessary to consider the fact that completeness of karst assessment of small territories by structural-tectonic criterion often depends on a technogenic factor, namely on technogenic leveling of a relief, density of the

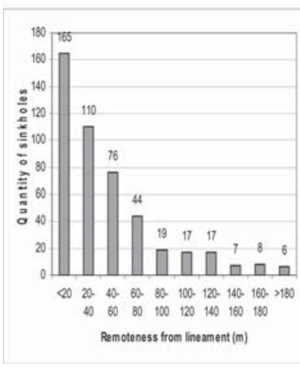

Figure 2. Ratio of remoteness from lineament axial zone (axis X) to number of karst collapse (axis Y).

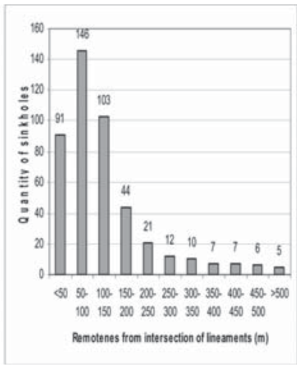

Figure 3. Ratio of remoteness from lineament intersections (axis X) to number of karst collapse (axis Y).

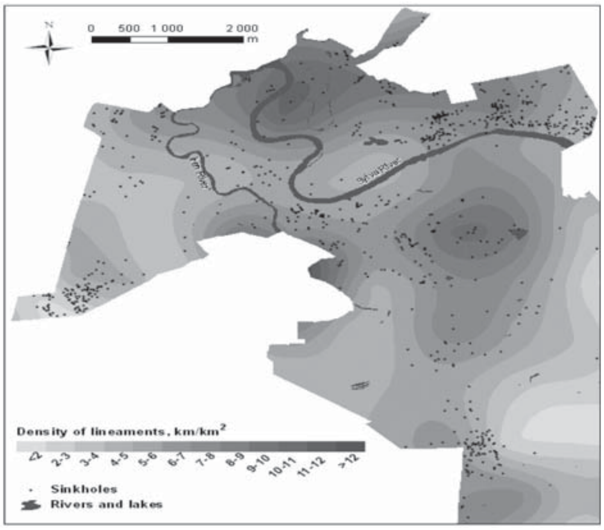

Figure 4. Sinkholes allocation concerning lineament linear density within Kungur territory (Western Urals, Russia).

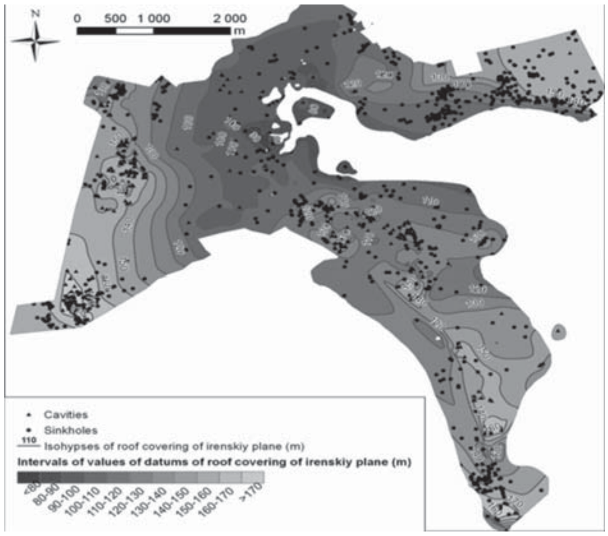

Figure 5. Ratio of sulphatic deposits roof depth of the irensky horizon to sinkholes in Kungur territory (the Western Urals, Russia).

Table 1. Prognostic equations of morphometric parameters of karst forms in relation to lineament indicators.

Indicator	Prognostic equation*
Linear density	$d = 0{,}7816Ll^2 - 1{,}8103Ll + 1{,}0962$
Number of intersections	$d = -0{,}1876\ln(Kl) + 0{,}0559$
Block size	$d = 0{,}9392B + 0{,}0101$
Remoteness	$d = 0{,}8155e^{-2{,}6424U}$

* Notation conventions: *d*—prognostic mean diameter, m; *Ll*—lineament linear density, *Kl*—number of intersections of lineaments, *B*–block size, *U*—remoteness from lineament.

construction objects that make interpretation of data of remote sensing more complicated.

Under lineament analysis the most rational is comparison of a spatial ratio of the revealed lineament to surface karst forms: karst suffusion sinks and dolinas in the form of combined one-large-scale maps (schemes) of lineament linear density on conventional unit of the area and an areal binding of the recorded sinks and dolinas or maps of karst piping sinks density and maps of dolinas density to an identical conventional unit of the studied area (Fig. 4).

Zones of the increased lineament linear density, allocated in the studied territory, are identified with disjunctive borders of tectonic blocks. Such borders can be presented by a series of small explosive damages or a monolithic fault structure with small amplitudes of shift of boards of tectonic blocks. The degree of spatial coincidence of the increased lineament density zones and faults with subvertical shift is usually high. Relatively raised blocks, as a rule, are characterized by higher energy relief values.

Under visual comparison of distribution of lineament linear density zones and units of an intensive karst occurrence the connection of the latter to zones of lineament linear density zones in the range of their average values can be clearly traced. This situation is confirmed by experience of an assessment of a spatial ratio of disjunctive dissociation to karstification within various regions of classical development of both sulphatic, and carbonate karst.

Any of the allocated lineament zones are connected, directly or indirectly, with the relevant systems of tectonic fissures. In other words, the allocated lineament zones can be interpreted as the zones of local permeability of a karstified massif, the zones of localization of ground waters drain under condition of active water exchange. Increased lineament linear density zones are the weakening massif zones, characterized by a higher degree of fractured-cavern (fractured-karstic) permeability, and consequently by a higher degree of subsurface karst forms potential development.

5 ATTRIBUTES OF A SPATIAL RATIO OF GEOLOGICAL CUT TYPES TO SUBSURFACE AND SURFACE KARST OCCURENCE

Karst research practice attests that conditions of a rocks bedding, namely the spatial combination of soluble and insoluble layers, is one of geological criteria of karst assessment.

The analysis of a massifs structure containing karstified series of rocks, allows to allocate typical litologic complexes in their compound, which spatial combination often defines karst type, its morphological attributes, subsurface and surface distribution form, and finally degree of stability of the territory.

Any of allocated types depending on specifics of an engineering construction can be estimated as "moderate hazardous". Considering modern conception of karst hazard criteria (existence and formation of dolina forms of large transverse cuts), the most hazardous, with relation to development of sudden dolinas, are situations when sedimentary semi-rocky layers lie on karst rocks or when karst sections outcrop and are presented by stratifying deposits of various dissolution intensity (carbonate and sulfate, sulfate-carbonate and other types). In this case the fissured roof facilitates a selective leaching with formation of arches or flat overlappings which create prerequisites to a catastrophic collapse.

Allocation of subsurface karst phenomena concerning allocation of types of cuts has almost similar character, as allocation of surface karst forms.

6 RATIO OF BLOCKING DEPOSITS CAPACITY TO SURFACE AND SUBSURFACE KARST FORMS

The deposits capacity which block karstic rocks and lithology of these deposits control allocation of surface and subsurface karstic forms. Blocking deposits capacity data, their lithological attributes, condition in combination with spatial allocation of karstic forms are one of the geological criteria of karst assessment within a concrete terrain.

To analyze influence of covers on karst development it is expedient to do quarternary covers capacities mapping and total covers capacities mapping of all present lithologic-stratigraphical types of deposits up to the roof of karstic rocks. These maps have different prognostic value.

Karst assessment has to be based on the analysis of blocking complex capacities. As a rule, territories with development of a blocking deposits complex by capacity 50 m and more correspond to a low degree of karstic forms occurence, and territories characterized by cover from 1 to 10 m or its absence correspond to a very high one.

For example, under conditions of territories with carbonate and sulfate karst development in Priuralie (Russia) where the capacity of solikamsk blocking deposits is less than 50 m (at the average capacity of the horizon 105 m), surface karstic forms develop everywhere regardless geomorphological characteristic of sites with their maximum occurrence in river valleys and in arches of tectonic elevations. Dissolution of sulphatic packs to the maximum degree—gypsum and anhydrites of irensky age results from a contact between blocking deposits moderate water impermeable (a local clayey aquiclude, rather low permeable pro-layers), in a zone of dynamic changes of subsurface waters level, a contact with spreading packs of carbonate rocks and carbonate sections of the philippovsky horizon.

The most vivid description of lithologic-stratigraphical control of a karstogenetic environment can be given within Kungur territory where the disposition of cavities in a cut of sulfate-carbonate section can be characterized by two situations: 1) cavities are located in a near-bottom zone of a glacier cave pack directly spread under by philippovsky dolomite; 2) cavities are located in a near-roof zone of the glacier cave pack blocked by rocks of nevolinsky pack. At any disposition of cavities the safety of the rocks containing a cavity, is worse, than the safety of rocks in intercavernous space, and rocks are characterized by a higher content of secondary minerals, silicates, increased, visually determinate porosity and cavernosity.

Almost the same situation with an influence of covers capacities is characteristic for the territory of Dzerzhinsk in Nizhny Novgorod Region (Central Russia). Here the analysis of the quarternary deposits capacity map (QI-IV) with surface karstic forms allowed drawing a conclusion that allocation of almost all karst-suffusion sinkholes is limited to the capacity of deposits of QI-IV to 45 m. Those territory units where the capacity of quarternary deposits exceeds 45m, sinkholes have no development. More than 90% of dolinas were developed in compartments with quarternary deposits capacity to 30 m. As applied to radical differences of rocks, blocking (shielding) karstific section under quarternary deposits, special value have zones of paleo-washout, fixed according to local decrease of their capacities (to 10m) or their complete denudation. In this case the role of the shield is performed by clayey deposits of the Tatar layer (P_2t). In particular over these zones of washout in quarternary deposits the majority of karstic-suffosion sinkholes fields is formed. We should note the fact that almost all dolinas are spatially bound to the places of washout of the Tatar deposits "shielding" a karst rocks roof where the "shield" capacity doesn't exceed 10 m.

7 RATIO OF KARST ROCKS SUBSURFACE RELIEF TO SURFACE AND SUBSURFACE KARST FORMS

Practice shows that a basic estimative attribute in the "closed" compartments under conditions of slight occurrence of surface relief elements is the "underground" relief—a karst rocks roof relief, and in particular, its elements: inselbergs (slopes and peaks), linear and flat depressions, saddles between ilsenbergs. The roof depth bedding of karstic section reflects attributes of a subsurface relief.

Morphological attributes of surface or covered (paleo-) karst macrorelief are generally caused by two types of heterogeneity of a massif structure: litological (structural and textural) and structural-tectonic (mainly fissured). It is obvious that in prevailing number of cases the karst rocks roof relief is a reflection of fissured massif structure differentiating the degree of water permeability, that localize surface and subsurface water that finally determines dissolution intensity and localization of cavities in a layer, and sinkholes in blocking deposits. Researches of ratio of density allocation of fissures to elements of a buried relief showed that depressions correspond to morphologically significantly dissociated compartments, saddles between inselbergs to moderate dissociated, inselbergs—to low dissociated.

It should be noted that large-scale karst zoning using attributes of a buried karstic relief as a basic characteristic is effective equally for massifs of sulphatic, sulfate-carbonate, and carbonate structure. Peculiarities of allocation of karst forms, which determine heterogeneity of terrain stability concerning elements of a buried karstic macrorelief, are almost common to the listed lithological types. Inselberg slopes and depressions (especially of linear type) are characterized by the highest density of cavities, on inselberg peaks cavities are absent as a rule.

The analysis of spatial allocation of subsurface (cavities) and surface (sinkholes, collapse lakes hollows) of karst forms testifies their connection to certain forms of a buried relief of the irensky horizon roof (fig. 5).

The absolute majority of the cavities disclosed while drilling which form congestions, is related to two types of a relief: cavities within saddles and cavities within a bottom of moderate steep inselberg sides—in places of their joint with an adjacent trough edge. The cavities in near-edge zones of a trough were recorded in isolated instances only.

Karst sinkholes spatially gravitate towards troughs, being often grouped as "discharged" chains focused from a trough to their center, possibly tracing faults that were hydrogeologically active during a certain period of a karst formation. Similar chains of sinkholes, however more dense, almost adjoining by sides, are characteristic for the narrowest sites of saddles. Here chains of sinkholes are focused in a cross of saddles strike. Rather izometric brinks of sinkholes, without obvious spatial orientation, are characteristic for near-sides sites of saddles in their external parts in relation to the depression center.

Subsurface karst forms and zones of the destroyed rocks are grouped in transition places

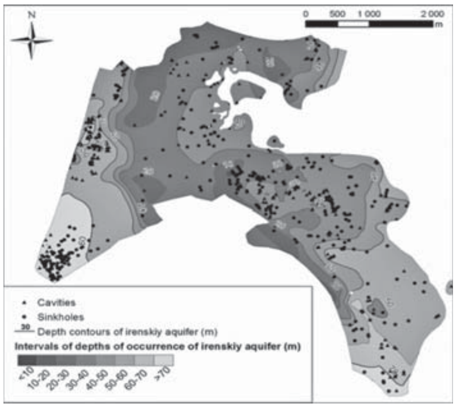

Figure 6. Distribution of karst forms to background of change of depth bedding of waters of irensky horizon.

from heights to minor saddles, having primary development in saddles close to linear forms.

It should be noted that within the territory of development of a "pure" carbonate karst, in particular within limestones of the Western Ural rugosity zone, the spatial relation of surface and especially subsurface karst forms (cavities) to elements of a buried relief is shown particularly vivid. Specifically, cavities are strictly bound to linear lowering of a relief, their axial zones.

8 LEVELS OF UNDERGROUND WATERS, THEIR CHEMISTRY AND KARST OCCURRENCE

While analyzing karst of the territory it would be efficient, along with an assessment of the geological or structural and tectonic factors defining potentiality of development of the deformation phenomena, to assess prognostic ability of particular hydrogeological phenomena of the regional and local rank connected first of all with dynamic changes of level and chemical modes of underground waters.

In massifs of karstic rocks there is an effect of local dynamic changes of the hydrogeological parameters, spatially connected with zones and sites of the increased density of fissures, breakage, faults zones. The effect intensifies within the areas of neotectonic activity. Here specific water inflows reach maxima, the mineralization of underground waters sharply raises. Changes have a wide range of the periods, including intra-day.

As a result of the conducted researches it became obvious that the karst prediction has to be based on the revealed local regularities of dynamic changes of parameters of a water abundance and a chemical composition of the underground waters which are at the same time an indicator of activity of hydrogeological processes, including processes of an underground erosion and dissolution. Territorially places of similar changes are sites and zones of potential development of underground karst cavities and, as a result—emergence of karst (karst suffosion) collapse. In practice, the sites, characterized by hydrogeological and hydrogeochemical parameters with short cycles of variations (sites of an unstable chemical mode, sharp changes of water level), localize sites of potential collapse hazard in solving problems of prognostic constructions.

The results of drilling testify that the depth of underground waters of the irensky water-bearing horizon in the territory of Kungur city on the average fluctuates in the range of 25,0–40,0 m, increasing in the direction to high terraces to 70,0 m and more. Relatively shallow from a land surface the waters of the irensky horizon underlay in the interstream area of Sylva and Iren rivers (values of hydroisobaths –20,0 m and less).

The maximum quantity of the recorded karst occurence inclines to sites of deep location of level of underground waters of the irensky horizon in two intervals: 20,0–40,0 m (especially for karst collapses); 20,0–40,0 m and 50,0–70,0 m for karstic cavities (fig. 6).

Spatial comparison of sites to various intensity of development of karstic cavities and the sites characterized by various degree of a mineralization of waters of the irensky horizon testifies that the majority of disclosed karstic cavities is revealed within sites where waters with a mineralization from 2,0 to 4,0 g/dm^3 are widespread.

The number of cavities fixed while drilling sharply decreases on sites with higher or lower values of mineralization. Similar regularity is characteristic for distribution of karst collapses as well. Territorial distribution of karst funnels also submits to this regularity, but in less explicit form. The number of karstic deformations in the form of funnels changes towards relative increase on sites where waters of the irensky horizon are characterized by values of the general mineralization in the range from 2,0 to 4,0 g/dm3 and (fig. 7) higher.

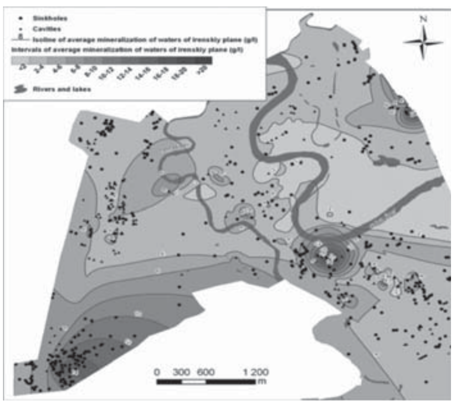

Figure 7. Distribution of karst forms to background of waters mineralization change of irensky horizon.

9 CONCLUSIONS

Summarizing premise it becomes obvious that the elements of explosive tectonics recorded on lineament, are a type of a geological cut as well as of capacity of integumentary deposits, and elements of subsurface relief of a karst rocks roof control allocation of surface and subsurface karst forms to various degree, model subsurface space and have to be considered while conducting karst assessment of a territory.

The listed factors, being criteria of the geological and structural analysis have to be considered in a complex, as they supplement each other, and form in aggregate the geological situation in which karst process develops.

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