Geological risks, formation and assessment in urbanized territories in Russia

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Abstract: In large cities hazardous geological processes usually develop rapidly due to increased anthropogenic influence, even if they don't occur under the same conditions in nature.

During assessment of hazards and risks in cities it is necessary to assess both natural and anthropogenic factors, because usually anthropogenic factors have the main role in the development of hazardous geological processes. Hydrodynamical and thermal balances in cities differ greatly from ones in the countryside. Also, in urban territories groundwater levels change greatly and such processes as underflooding, loess subsidence and many others start to develop though they are rather rare within unsettled territories.

New methods of probabilistic-deterministic hazard and risk predictive assessment for karst, landslide and other hazardous geological processes with specific examples are characterized in this paper.

The areal intensity of surface deformations (m^2/km^2 a year) is used as the main index of karst hazard and physical risk of territory losses. Physical risk determined in such way is the basis for quantitative assessment of economic (\$/year, \$/km^2 a year), social (person/year), individual (person/person a year) and ecological (km^2/year, species/year, \$/km^2 a year and etc.) risks.

Résumé: Dans les conditions de la charge technogène élevée sur les territoires urbains commence un développement actif des processus géologiques dangereux qui ne se forment pas dans les conditions pareilles hors des territoires urbanisés.

En évaluant les dangers et les risques sur les teritoires urbains il faut évaluer non seulement les facteurs naturels mais encore les facteurs technogènes, puisque ce sont précisément les derniers qui exercent une influence déterminante sur le développement des processus géologiques dangereux sur les territoires urbains. Par comparaison au territoire non-peuplé, dans les villes changent le bilan hydrodynamique et celui de température, change le niveau des eaux souterraines, commence le développement des processus qui presque ne sont pas développés sur les territoires non-peuplés.

L'article examine la méthode nouvelle de l'évaluation de prédiction probabilistique et déterminée des dangers et des risques survenant des processus karstiques, processus de glissement ainsi que des autres processus géologiques dangereux.

Pour l'indice intégral principal du danger ou du risque physique de perte du territoire la méthode probabilistique et déterminée utilise l'intensité aréale de la déformation de surface terrestre (m^2/km^2 par an).

Le risque physique déterminé de cette façon constitue la base pour l'évaluation quantitative des risques de perte économiques (dollars/an, dollars/km^2 par an), socials (personnes/an), individuels (personnes/personnes par an) et écologiques (km^2/an, individus/an, dollars/km^2 par an, etc.) survenant des processus géologiques dangereux.

Keywords: Geological hazards, risk assessment, engineering geology, land subsidence

INTRODUCTION

Risk-based systematic studies of geological and other natural hazards, as well as catastrophes caused by these processes have been carried out since the 1990s. Studies concentrated initially on determining the theoretical basis and techniques for assessing risk posed by different natural hazards. The first examples of risk assessment at local, regional, and federal levels were obtained using social (persons/year), individual (persons/persons/year), economic (\$/year) and other quantitative indices of possible losses (Ragozin 1994, 1998, Ragozin & Yolkin 2004).

At the same time, the legislative and standardized working practices for natural risks assessment were formulated. As a result, risk assessment is now a necessary part of engineering surveys for all kinds of construction. In addition, under the Federal law of the Russian Federation "About technical regulation" dated December 12, 2002 184, the safety of any development, including buildings, construction, and adjoining sites, should be defined using a risk-based approach. It is intended that this new probabilistic system of safety assessment or reliability of structures should be incorporated in technical regulations and replace existing building rules (similar to Eurocodes) not later than 2010. By adopting these measures in Russia and in many other countries of the world, quantitative risk assessment becomes the basic mechanism for making scientifically sustainable decisions aimed at a reducing the risk to people and property. However, there remain some unresolved theoretical and practical questions relating to the risk-analysis of geological and other natural hazards that are crucial for protection, and these are introduced in the present paper.

TECHNOLOGICAL AND NATURAL HAZARDS IDENTIFICATION AT RISK ASSESSMENT

The incidence of geological hazards in urbanized areas depends partly on natural events but is often exacerbated by human influence. It is the anthropogenic factors that are partly responsible for the higher temporal and spatial distribution of these processes as compared to the intensity recorded in undisturbed ground. Areas previously unaffected by geohazards are now experiencing problems. For example, less than 1% of urbanized areas in Russia were affected by rising groundwater levels in the late 1950s; currently the figure stands at about 20%. During the last ten years, areas experiencing flooding from rising groundwater levels have grown by about 35-40%, and new areas where these affects are now being observed have increased by not less than 5% (Ragozin 2003). Flooding is accompanied by related processes including landsliding, karst-suffosion, loess collapse, seismicity and other engineering geological processes.

There are several factors responsible for the problems noted above. They include: leakage from water-bearing lines - now reaching 50% and more in certain Russian cities; transport vibration effects; static and dynamic loading by buildings and structures; electromagnetic fields - responsible for increased corrosivity of soil; and differing thermal regimes in cities and other settlements. So, for example at present, the process of karst deformation has increased within urbanized territories as a result of uncontrolled pumping of groundwater and large-scale seepage from water-bearing pipelines. Until the 1960s, karst collapses within Moscow were unknown, but during the last 30 years more than 40 collapses have been recorded. In 1969 and 1977, in the northern part of city, they destroyed three houses. The total economic loss from these disasters is equal (at present-day prices) to not less than 10 million dollars. The greatest hazard from such collapses is recognized in urbanized territories where the population may be living close to dangerous installations (chemical, nuclear etc.), and where destruction or even partial collapse of such structures could lead to mass injuries. It was only by chance, that a large karst collapse that occurred on July 15th, 1992 in Dzerzhinsk city, took place at a time when the buildings in the vicinity were unoccupied. The collapse, 30 m in diameter and 20 m deep, destroyed one of the buildings NPO "Dzerzhinskhimmash" constructed in the early seventies. No karst hazard assessment had been undertaken at the time ths building was constructed. The cost of this failure was 1.7 million dollars (Ragozin 2003).

The hazards posed by such processes are substantially higher in terms of social, economic, and other costs, because the population density and national wealth are concentrated in these areas rather than in less developed regions of the Earth.

The identification of natural and man-induced hazards for the purposes of risk assessment differs considerably from the traditional and comprehensive engineering investigations aimed at the prediction of natural hazards. The main distinction consists in performing special studies, which allow us to identify and classify natural hazards of different genesis by means of age determination of events that have occurred in the historical and recent geological past using radiocarbon, dendrochronological and other dating methods.

Another distinction is related to the necessity to develop synergetic models and possible scenarios of the primary and secondary hazards and their outcomes in different situations, similar to those shown in Figure 1. The scientific basis for forecasting natural and anthropogenic hazards and risks of losses caused by such processes is impossible without construction of models of this type.

PROBABILISTIC-DETERMINISTIC PREDICTION OF GEOLOGICAL HAZARDS

A quantitative estimation of geological risk in the considered areas begins with the identification (determination of possible formation) and prediction of how a particular geological hazard will manifest itself in response to natural and man-induced factors (conditions and processes). This should also take account of the serviceability (lifetime) and vulnerability of the facility (risk recipients). At this point, the main difficulty lies in predicting not only the natural effects but also the anthropogenic impacts on the geological environment (leakage from water-bearing lines, thermal fields, loads of buildings and structures, etc.). At present, this predictive information is an obligatory requirement to assess and help substantiate the possible damaging consequences of anthropogenic impacts on the geological environment. These may take the form of changing loads, altering rock physico-mechanical properties, or the initiation of new geological hazards or intensification of existing ones. In many cases, the results of such predictions will be ambiguous. To eliminate this ambiguity, it is necessary to develop and use new complex probabilistic-deterministic methods. Such methods should take into account synergetic relationships i.e. the possibility of mutual intensification or attenuation of hazards (see Figure 1).

Probabilistic-deterministic prediction consists of using revealed deterministic and statistical laws and procedures with respect to the occurrence of geological hazards and the corresponding calculation models, taking into account a probabilistic character of external driving forces (regime-forming factors), their possible combinations and heterogeneities of the geological environment, with subsequent probabilistic interpretation of the obtained results. At present, the proposed integration of the methods allows consideration in predictions of both regular and random development of the processes using most substantiated and strong aspects of deterministic and probabilistic-statistical methods for estimating these processes. These methods represent rather well developed and repeatedly tested procedures for determining a possibility of formation, scales, character, and intensity (destructive force) of different hazardous geological processes in specific volumes of the lithospheric space (probabilistic methods) and a more valid consideration of the variability of external effects and corresponding time evolution of the processes (probabilistic-statistic methods).

Let's explain the statement mentioned above using a particular example of landslide prediction with reference to slopes composed of clay bedrock in the area of Tsimlyanskoe Water Reservoir. How is the stability of these slopes usually assessed?

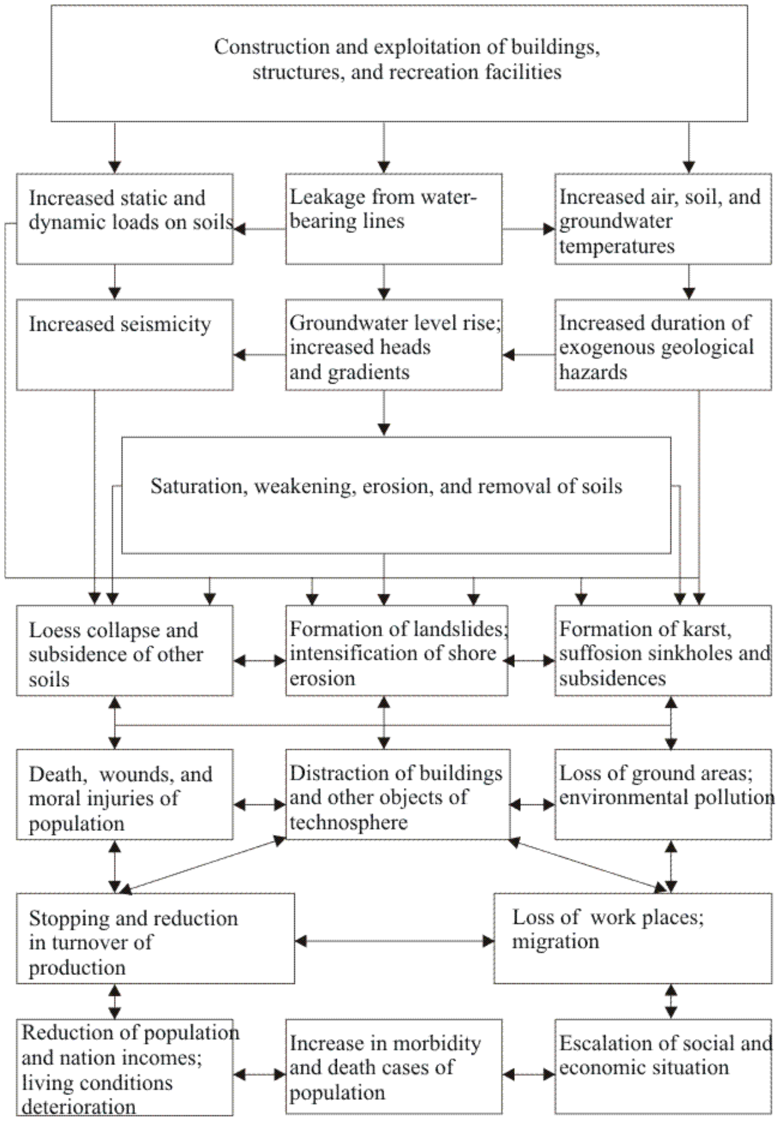

Figure 1. The synergetic model of formation, mutual intensification and transformation of geological hazards within urbanized areas

As rule, engineering investigations are carried out in the summer. During this season, the coefficient of shearing strength of slope rocks with reduced moisture is determined and the safety factor (SF) of a slope is established. Sometimes, the specified operation is made with regard to reservoir bank erosion characterized by the curve 1 in Figure 2. According to this curve, the safety factor (SF) will be above 1 for more than 100 years. Additionally, in some cases, the susceptibility of the slope stability to seismic impact can be examined, which, in turn, can lower the SF by 0.2 in this example. From these measurements, a conclusion about the general stability of the slope over the next several decades can be made. However, in practice, the stability of the slope may be affected in the first year by a seven-point earthquake in springtime, when the moisture content of the slope deposits is at a maximum. Only due to seasonal moistening of slope rocks, SF decreases by 0.1 annually (Figure 2). Hence, the final recurrence of the seven-point earthquakes in the considered case is equal to 1 time in 200 years that corresponds to annual probability of realization – 0.005. Seasonal moistening of a slope is recorded during 2 months in a year. Then, the probability of realization of this event per a year is 2 : 12 = 0.17 and, respectively, the final probability of landslide deformation is calculated by multiplication of probabilities of two independent events (i.e., simultaneous occurrence of two triggering factors-processes) – 0.17 0.005 = $8.5 \cdot 10^{-3}$. The additional account of another factor of landsliding, or abnormal moistening of slope rocks in high-water years, increases the total probability of disturbance of slope stability in the first year to $9,3 \cdot 10^{-3}$ (Figure 2).

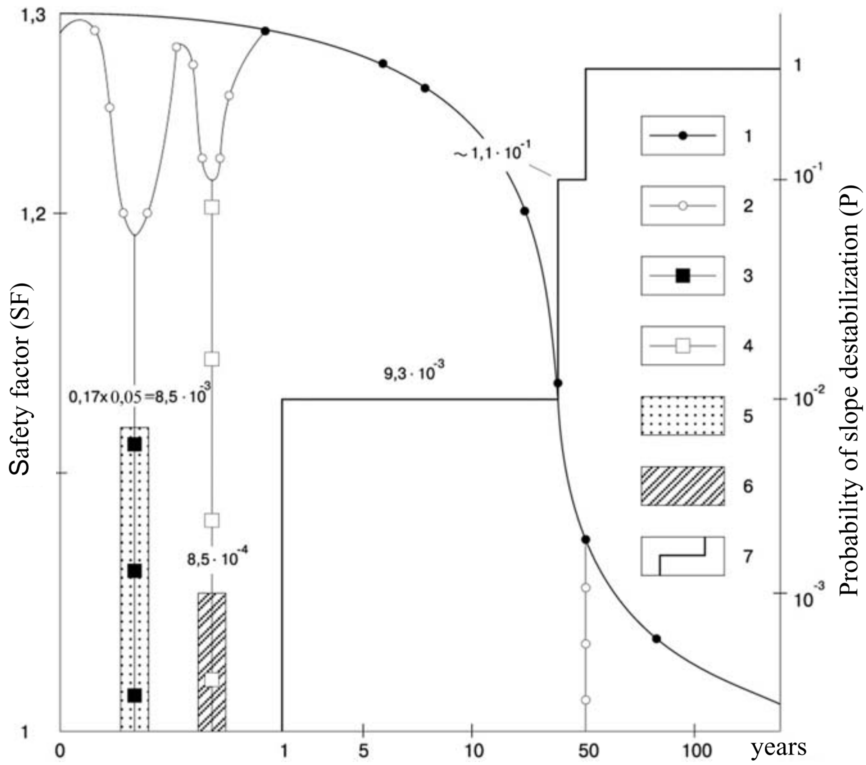

Figure 2. Synergistic probabilistic-deterministic model of landslides formation
The changing of safety factor of a slope under influence of various factors and their synergistic combinations: 1 - abrasion; 2 - the factor 1 and seasonal moistening of a slope with probability of realization within a year = 2:12 = 0.17; 3 - factors 1, 2 and the seven-point earthquake with = 0.005; 4 - factors 1, 2, 3 and abnormal moistening in high-water years with = 0.1. Probability of slope destabilization under the various combinations of factors: 5 - abrasion, seasonal moistening of a slope, and earthquake; 6 - abrasion, long-term moistening of a slope, and earthquake; 7 - all factors.

By simultaneously taking account of several factors, namely, erosion of the slope base, seasonal and long-term moisture content of the slope rocks, as well as the impact of a seven-point earthquake, the probability of slope failure over time can be estimated as shown in Figure 2.

We particularly note here one of the basic features of synergism, or synergetic interactions of the several factors, sometimes, having different genesis and giving rise to the main process. None of the factors in the case considered above, acting separately, could not lead to landslide formation during the a 50-year period. However, their combination can cause landslide deformations in the first few years with small probability. Thus, the synergetic factors similar to those characterized above are not only the necessary condition for development of the geological processes but they can also influence the time of their formation. All the synergetic sets of factors should be determined for prediction of these processes, as well as when carrying out the subsequent analysis of risk of possible losses.

A similar approach to prediction and the assessment of natural risks is appropriate for landslides, karst, subsidence, mudflows, erosion and other geological hazards. In all cases, the influence of external factors needs to be taken into account, among which the leading role often belongs to hydrological and meteorological processes.

A detailed analysis of these processes is especially necessary in urbanized territories, where mid-annual temperatures of air and soils are usually 5-7 ºC higher than those in rural settings. These factors taken together with anthropogenic-induced flooding of territories increase the duration of development and, accordingly, the degree of activity of hazardous geological processes. Sometimes, the abnormally high temperatures within urbanized territories can become a principal cause of destructive winds beneath colder cyclonic air masses, as occurred, for example, on July, 20-21st, 1998 in Moscow. As a result of this natural disaster, over 200 people were injured and two people died in Podolsk and Lyubertsy. About 2500 houses were damaged to a variable degree, lighting was damaged in 193 streets, and more than 110 000 trees were felled in Moscow. The direct economic damage was equal to 160 million dollars (Ragozin 2003).

VULNERABILITY ASSESSMENT

By vulnerability we mean the tendency of any material object to lose its natural or assigned properties under the effect of hazardous processes of a certain genesis, intensity, and duration (Ragozin 1994, 1998). We distinguish four main types of vulnerability depending on the type of loss: physical, economical, social or environmental.

In the elementary case, it can be directly determined from the following equation

$$V(H) = n_i/n \qquad (1)$$

where V(H) is the object vulnerability in any sphere of consideration of possible losses (fractions of unit, f.u.); n_i – is the number of destroyed and damaged elements by hazard H or the cost of these elements in object; n – is the total number of elements or the total cost of these elements before this event.

Using this formula, we can determine the vulnerability of different facilities for the zone of the Spitak earthquake of magnitude 8-9 (Armenia, 1988). About 365 villages and 120 000 dwelling houses with about 1 million residents fell into this zone. As a result of the earthquake, 58 settlements and more than 61 000 houses were completely destroyed. About 25 000 people perished. According to (1):

- the physical vulnerability of settlements to such an earthquake is 58 : 365 = 0.159;
- the vulnerability of dwelling houses is 61 : 120 = 0.51;
- the population vulnerability is equal to 0.025.

For comparison, note that during the earthquakes of similar intensity in Neftegorsk of 27.05.1995, the vulnerability of 3-5 storey houses was 1, and that of the population was 2 : 3.45 = 0.58.

At present, empirical statistical tables of vulnerability of buildings and their occupants are developed for application to earthquakes, karst collapses and ground subsidence, and underflooding of territories etc (Ragozin 2003). Until recently, the vulnerability assessment remains a poorly developed element in the general scheme of natural risk analysis.

THE BASIC PARAMETERS OF RISK ASSESSMENT

By geological risk we mean the probabilistic index of one or more geological hazards established for a particular object at risk as to the possible losses in various spheres for a given time period (Ragozin 1994, 1998).

The substantial generic differences between natural hazards, which determine the character and scale of destruction of different facilities or targets, can be reduced to two main mathematical models of risk formation: from single-feature episodic processes to processes occurring repeatedly in a certain region. For the territories subject to single-feature episodic processes, the simplest risk type is destruction of an area by landslides, mudflows, earthquakes, and floods. The typical examples of repeat processes are abrasion, underflooding of territories, etc.

$$R_0(H) = P^*(H) \cdot V(H) \cdot D \qquad (2)$$

$$R_p(H) = V_n \cdot P(V_n) \cdot V(H) \cdot d_s \qquad (3)$$

where R_0 (H) and R_p (H) - risk of losses from single-feature episodic and permanent hazard, respectively; P^* (H) - is the recurrence of episodic hazard (cases per year); V (H) - is the vulnerability of object to hazard , determined from (1); D - is total damage from hazard within a sphere of losses fixation; V_n - is the areal rate of process development (hectares/year); P (V_n) - is the probability of this rate realization; d_s - is the density of national wealth ($/hectares).

These basic formulas with reference to assessment of social, individual, economic, and other risks of losses are cited in the following investigations (Ragozin 1994, 1998; Ragozin & Yolkin 2004).

As has been shown above, the geological risk assessment should be carried out at all stages of engineering surveys for construction. Firstly, the physical risk of object destruction by single hazards is determined, and then the risks of losses in various spheres.

Below are some parameters which can be used as a quantitative measure of natural risk depending on the scale of such estimating.

- The cost episodic, social or ecological risk - the possible damage from hazard of certain type, intensity and duration of action ($, per., the destroyed area etc.);
- The event risk - frequency of realization of such damage (cases/year);
- The event risk of a natural extreme situation of the certain degree of heaviness (cases/year);
- The physical risk of object destruction (i.e., the territories with all the objects of economic, population and surrounding environment) by single-feature episodic processes or permanent processes of the certain intensity (m^2/year, $m^2/km^2\cdot$year etc.);
- The economic risk of total ($/year) and specific ($/$km^2\cdot$year) losses of object from the same hazards;
- The social (persons/year) and individual (persons/persons·year) risk of destruction with a certain outcome in the considered territory from the same hazards;
- The ecological and population risk of destruction of environment and individual representatives of fauna and flora (ha/year, $/year, $/$km^2\cdot$year, animals/year, etc.).

The event risks of disasters as well as individual and specific economic risks are the most used risk indexes on the federal and regional scales of Russia, which are allowed to carry out comparative analysis of potential negative situations.

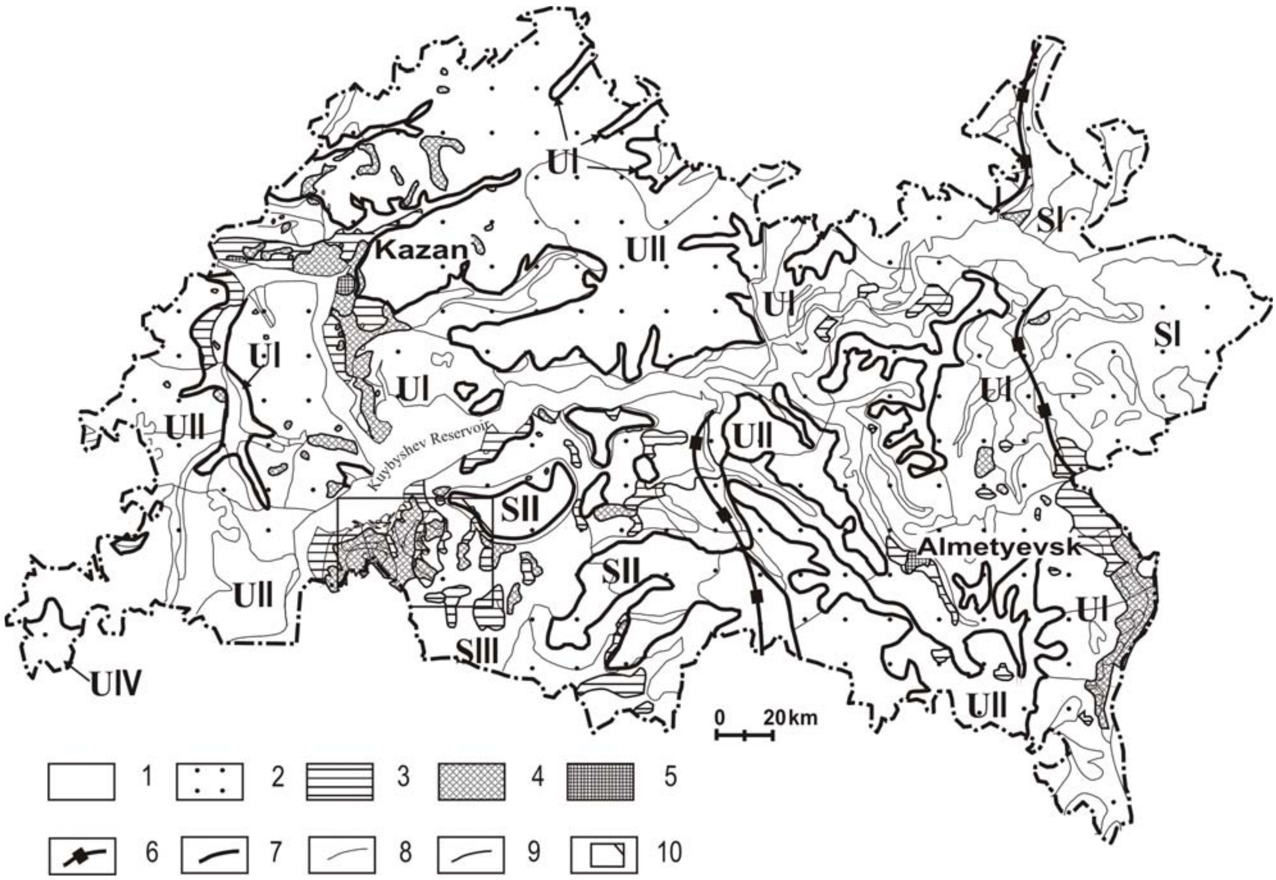

Figure 3. Karst hazard map of the Tatarstan Republic
Territorial karst hazard categories (areal intensity of karst deformations, $m^2/km^2 \cdot year$): 1 - non-hazardous (0); insignificantly hazardous: 2 - (<0.01); 3 - (0.01 – 0.1); 4 - slightly hazardous (0.1 – 1); 5 - moderately hazardous (1 – 3). Boundaries: 6 - of territories with uplift (U) and subsidence (S) neotectonic movements, which are equal to the regions of the 1st order; 7 - of stratigraphic and lithologic complexes of karst-prone bedrocks, which are equal to the regions of the 2nd order: complex of sulfate-carbonate rocks (I), complex of carbonate-terrigenous rocks (II), complex of sulfate-carbonate-terrigenous rocks (III), complex of carbonate-terrigenous rocks (IV); 8 - of taxons of the cross tripple typological zoning; 9 - of groups of NTS of the second order differing in karst hazard categories; 10 - a key site of detailed investigations.

The quantitative assessment of karst hazard and risk at a regional level (1:500 000 scale) was undertaken during 2003-2004 in the area of the Republic Tatarstan (Ragozin & Yolkin 2004). The forecast values of karst hazard, characterized by areal square intensity or, in other words, the physical risk of territory destruction by karst collapse were ranked according to one of six categories (Figure 3). It is necessary to note that karst physical risk in this form is a basis for assessing other kinds of risk (economic, social, and ecological). The example of a social risk map for karst area is presented in Figure 4 (1:200 000 scale).

An analysis of the map presented in Figure 3 shows the varying susceptibility of the Tatarstan Republic to karst collapse. Throughout the territory (91.5 %), the areal intensity is less than 0.1 m^2/km^2 /year, i.e. insignificantly hazardous category. Slightly hazardous and moderately hazardous territories cover 4.3 and 0.2 % respectively. The areal intensity of collapse formation varies from 0.11 to 0.92 m^2/km^2 /year in territories categorized as slightly hazardous. As a rule, these coincide with areas marginal to the buried and modern river valleys of the Volga and Kama and their inflows in the Aznakaevsky, Alekseevsky, Alkeyevsky, Arsky, Bavlinsky, Vysokogorsky, Zelenodolsky, Kamsko-Ustyensky, Laishevsky, Sarmanovsky, Spassky, and Yutazinsky districts. Within 4 % of the territory, located in the southwest of Tatarstan (Bouinsky, Drozhanovsky, and Tetyussky districts), karst collapse is unlikely because the susceptible bedrock is overlapped by terrigenous deposits (J_{2-3}; K_1) more than 100 - 150 m thick.

At the present time, the largest karst hazard (up to 1.6 m^2/km^2 a year) is specified for the territory of Kazan and others large towns. It is generally explained by man-induced influence, which has led to a change in the subsurface water regime and activation of anthropogenic karst-suffosion processes.

The results of social risk assessment (see Figure 4) suggest that the maximum risk (up to $1 \cdot 10^{-6}$ persons/persons/year) affects two settlements (Kuralovo & Ekaterinovka). The ranking is equal to the middle Federal level according to the general classification of individual natural risks of Russia proposed by Ragozin (1994), therefore it may be considered an acceptable risk in the current socio-economic conditions. Over the greater part of the assessed districts (Spassky & Alkeyevsky) the individual risk is at a low level (< $1 \cdot 10^{-8}$ persons/persons/year).

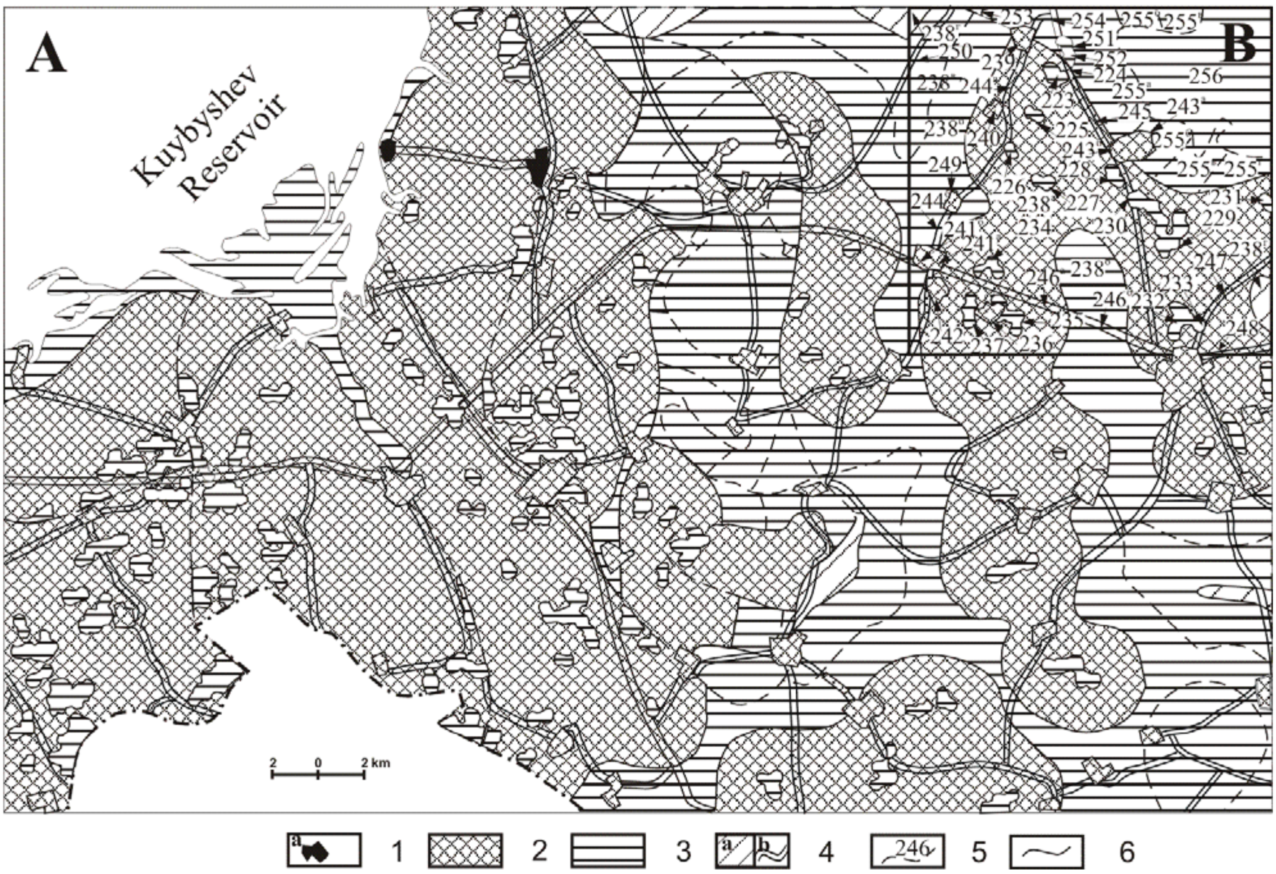

Figure 4. Fragment of the map of karst individual risk of Tatarstan (schematized (A) and total (B) versions)
Karst individual risk within areal (a) and linear (b) objects (persons/persons·year): average: 1 - $(1\cdot 10^{-7} - 1\cdot 10^{-6})$; small: 2 - $(1\cdot 10^{-8} - 1\cdot 10^{-9})$; 3 - $(1\cdot 10^{-9} - 1\cdot 10^{-12})$; 4 - $(<1\cdot 10^{-12})$. Boundaries: 5 - of the second-order NTSs (and their numbers) with different areal intensity of collapse formation, $m^2/km^2\cdot$year; 6 - of the second-order NTS groups of different individual karst risk categories. Note: The karst risk categories are presented according to the general classification of individual karst risks in Russia (Ragozin 1994).

Thus, the estimates of geological and other natural risks gradually become one of the main reasons for making scientifically substantiated administrative resolutions in order to prevent and (or) mitigate the negative consequences of different natural hazards in Russia and other countries. It is especially important to mitigate hazards in urbanized areas, because, at present, most of population and the main material values are concentrated here. Therefore, the damages caused by hazardous geological and other natural processes, reaching (in Russia) 80% of their total volume, are mainly observed in these regions.

CONCLUSIONS

The natural risk assessment and management of hazards has become a universally recognized problem during the last ten years. Until recently, the mechanism of mitigation and prevention of losses from natural hazards of different types was poorly researched. The practical experience gained in recent years needs to be collated in a way that can be applied systematically in different countries, and to a range of hazards. In Russia, a quantitative assessment of risk has been a prerequisite for engineering surveys for all kinds of construction since 1997 in accordance with legal and related control documents.

The large-scale application of a new methodology of risk-analysis and management of geological and other natural risks places the safety of the population, its facilities and the environment firmly on the agenda.

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