Development of a permanent geological environment model of Kazan city aimed to solve various engineering-geological problems (Russia)

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Abstract. The article discusses the composition, structure and operation principles of a digital geological environment model for the urban area located in the valley of a large lowland river (the Volga). The model is implemented in ESRI (ArcView and ArcGis) and MapInfo software environments. The basis of the model is the data on the composition and physical and mechanical properties of soils, the information about ground waters and industrial loads. The model has been used to conduct zoning of soil conditions, groundwater aggressivity to the materials of underground structures. Also, the areas of existing and possible exogenous geological processes (flooding, karst, suffusion, erosion, landslides) have been identified. According to the model, it is offered to evaluate the stability of geological environment to human impact using typification on the soil conditions based on the pre-zoning of water content and the degree of drainage. A new monitoring system of dangerous exogenous geological processes has been developed, the impact of exogenous processes on the residential buildings has been estimated, and, also, the analysis and evaluation of geological risks have been performed. According to the data on the composition, density and water saturation of soils, the stability of the ground bases to a dynamic impact has been estimated.

1. Introduction

Kazan is one of the largest industrial centers of Russia, the city with more than one million inhabitants and a millennial history. The city is located in the eastern part of the East European platform, within a complicatedly formed terrace complex of the large lowland river Volga. The upper part of the geological section is represented by alternation of the carbonate and terrigenous Permian rocks; they are erosively covered by sandy-clay sediments of the Pliocene and Quaternary, mostly, alluvial sands, sandy loams, loams and clays.

Complicated geomorphological and geological-hydrogeological conditions, as well as centuries of human impact on the geological environment predetermined the development of flooding processes, karst, suffusion, landslides, river and gully erosion, abrasion, subsidence of soils, chemical pollution of ground waters. Activation of these processes has led to the increase of accidents in industrial and residential assets. Therefore, there is a need for a monitoring system of exogenous geological processes, which would be based on a large-scale multi-layered graphic digital environment model (hereinafter, a GIS-model), corresponding to engineering-geological conditions.

The GIS-model is based on the data on geological and hydrogeological conditions of the city obtained during geological surveys, which have been carried out by various organizations, at scale of 1: 50 000 - 1: 200 000 (from 1961), satellite imageries and topographic maps, at scale of 1: 25 000 and 1: 50 000, data on the composition, physical and mechanical properties of soils (about a thousand wells), and, also, numerous scientific studies. As a part of the GIS-model, a detailed route survey has been conducted to explore geological processes on the territory of the Kazan city, as well as visual evaluation of the technical condition has been given for industrial and civil objects [1].

2. Composition and structure of the permanent model

Under the permanent environment model we understand a unified geoinformation system of the structured and interrelated conditions and factors corresponding to the status of geological space, which is transformed into its cartographic representation. Development of the model has been carried out in ESRI - ArcView and ArcGis environment, as well as in Easy Trace software. Later the model has been transformed into MapInfo environment. The model is a combination of the following blocks (databases):

«Soils&rocks» block is a database of points (1057 points). Primary information required both for modeling and forecasting is fixed to each point in the attribute table of the GIS-model: a type, genesis and age of soils, their physical and mechanical properties, depths of bottom and top, thickness.

«Groundwater» block is also a database of points (about three hundred points). An attribute table of the GIS-model contains information about water table depths and ground water chemical composition.

«Exogenous geological processes» block is a complex database, where a separate database corresponds to one exogenous geological process. The block contains point databases (suffusion, landslides), as well as linear (erosion, abrasion), and polygonal databases (karst, flooding, subsidence of soils). Attribute tables of databases contain information about the process activity. For such processes as karst, waterlogging and subsidence of soils the attribute tables contain information about the probability of activation.

«Technogenic load» block is also a set of databases (linear and polygonal ones). It shows the static load on the geological environment according to weight of buildings and structures, vibration loads from the movement of auto- and electric transport, a barrage effect of buildings, the areas of existing and possible leakage from the water communications (changes in the chemical and hydrogeodynamic regime of ground waters), the dissemination of technogenic soils with indication of their type and thickness.

On the basis of these four blocks (the primary data), as well as with the use of the existing medium-scale geological and hydro-geological maps and a series of engineering-geological routes, we have synthesized the following vector maps (1: 25 000): geomorphological, geological maps of the Quaternary and Pre-Quaternary sediments, a map of ground water chemical composition, and a map of water table depths. As a part of the GIS-model, a map of soil types has been formed. Zoning in compliance with soil conditions has been carried out by approximation of the data according to the nature of soil bedding to a depth of 30 m from the database of the «Soils&rocks» block. Borders control between areas has been carried out using geological maps. Totally, 29 types of soils are identified, which are combined into the following groups: A - various variants of interbedded sandy and clay soils; B - the types similar to group A, but with the presence of soil subsidence differences, C - soils, which contain rocky soils, in addition to disperse, D - soils, which contain peat and /or peaty soils [2].

«Deformation of structures» block is an additional database, which contains the deformed residential buildings, according to visual evaluation of their condition.

The developed GIS-model allows sorting the information, as well as performing statistical analysis, interpolation, spatial operations, forming complex queries to retrieve information from the database, making changes in the database. As a result, it is possible to get a set of new prediction maps, and to display the results in maps.

3. Main results

3.1. Comprehensive evaluation of engineering and geological conditions.

While using the "Master of spatial operations" application, the resulting GIS-model allows us analyzing the factors of engineering and geological conditions formation:

According to data on chemical composition of ground waters, and taking into account the criteria used in the Russian regulatory documents, the areas with various types of groundwater aggressivity towards materials of underground structures have been identified [3].

The areas of carbonate eluvium have been identified, a depth map of eluvial sediments top has been obtained (highly susceptible to dissolution and suffusion), and their thickness has been shown. Later, the information has been refined, additional laboratory investigations of carbonate eluvium have been conducted, which are discussed in a number of studies [1, 4].

New principles of urban areas typification based on the stability of the geological environment to human impact have been substantiated and developed. It is offered to implement zoning according to watering and drainage, at the first stage, and to assess the stability of the geological environment at the level of a soil type, at the second stage (as far as it contains the information about stable or unstable soils under certain drainage and water content). A certain type of technogenic impact has been assigned to each taxon in the attribute table of the database, in relation to which the geological environment is unstable. Also, possible geological processes "have been predicted" (a response to the technogenic impact), as well as the degree of geological environment stability. The data on buildings deformation have been compared with the data obtained at evaluating geological environment stability. This comparison allows revealing a clear accordance "calculated stability - volume and extent of structures deformation", which is not observed while using the other methods of evaluation [5].

The complexity of engineering and geological conditions has been quantified according to the criteria of the Russian regulatory documents. Quantitative analysis has shown that a significant part of the urban area is characterized by the geological conditions of complex (47%) and medium complexity (45%). It is, mainly, determined by hydrological conditions and the extensive development of geological processes. A significant part of the urban area is exposed to the development of waterlogging processes (25%). Also, the areas of karst-suffusion activation (4%), erosion (3%), and slope processes (3%) have been identified.

3.2. Monitoring of dangerous exogenous geological processes on Kazan territory.

Based on analysis of the GIS-model databases new observational sites and areas for the monitoring of exogenous geological processes have been identified (12 sites). The detailed study of the geological and hydrogeological conditions has been conducted within each area, as well as both a program of technical equipping with measuring instruments and a method of observation with time intervals have been developed. Economic feasibility is given for each type of observation [6].

3.3. Analysis and risk evaluation of the geological processes damage on the territory of the historic center of the Kazan city.

The availability of created databases has allowed conducting quantitative evaluation of a geological risk (physical, economic and social) due to the possible activation of exogenous geological processes in the historic part of the city. These risks have been evaluated by the method of IEG RAS involving some economic and statistical data for the city of Moscow. Additional block of the GIS-model has been developed to evaluate the economic risks. This block contains information about the number of storeys in buildings, the type of foundation, the cost and age of buildings. The database on population density at different times of the day has been formed to evaluate social risks. It is observed that the territory of the Kremlin hill is characterized by the maximum geological risk values due to the extensive development of karst-suffusion processes, high population density, and a sufficiently dense development (a physical risk - 1 incident / 10 years, the potential economic losses - $ 23 million, a social risk - 1 pers. / 1000 years) [7].

3.4. Evaluation of ground bases stability to a dynamic impact.

The GIS-model has allowed implementing the idea of city zoning based on the stability of the soil bases to a dynamic impact (sands to a depth of 15m are the most susceptible). Typical responses of sandy soils to the dynamic impact and typification criteria are shown in Table 1.

Table 1. Classification of sandy soils on dynamic instability.

Type of dynamic instability	Porosity coefficient, unit fraction		Water saturation, unit fraction
Postcompaction	pulverescent	>0,80	any
	fine	>0,75	
	gravelly, large and medium size	>0,70	
Decompression	pulverescent and fine	≤0,60	0÷0,5
	gravelly, large and medium size	≤0,55	
Accumulation of shear deformations	pulverescent and fine	≤0,60	0,8÷1
	gravelly, large and medium size	≤0,55	
Liquefaction	any		0,8÷1

As a part of the GIS-model, this idea has been implemented as the following sequence:

- Identification of the areas that contain sands on a depth less than 15 m.
- Typification in accordance with the location of sands in section and in relation to groundwater table.
- "Binding" the data on the density and moisture content of sandy soils by transferring the data from the point objects of the «Soils & rocks» block to polygonal ones (the areas with a certain type of soils).
- Assigning the type of dynamic stability for the areas according to the specified criteria.

Performed zoning has shown that the dynamic instability of soils is the most typical for the complex of low terraces. All the sands located below the groundwater table are potentially liquefiable, regardless of their genesis, density and a particle size. Moreover, shear deformations accumulation and postcompaction are typical for a significant part of sands from the complex of low terraces, while decompression is hardly probable. The majority of sandy soils from high terraces complex is often resistant to the dynamic impact due to the high density and low humidity. Decompression (both for natural and technogenically altered sands) is typical only for some areas [8].

3.5. Geological evaluation of exogenous geological processes impact on the areas of residential houses building (Kazan).

In 2014 the Ministry of the Russian Federation for Civil Defense, Emergencies and Disaster Response compiled the list of the buildings ruining due to influence of exogenous geological processes (581 buildings on the Kazan territory). The list was formed according to the complaints of the citizens, who would like to get new apartments at the expense of the state budget. In order to identify the true causes of buildings and the surrounding area destruction, visual inspection of buildings was carried out, but it was not enough to make a final decision. It was necessary to carry out a full evaluation of engineering and geological conditions, but a very short turnaround time (2 months) and the low cost of the work did not allow us conducting necessary field and laboratory studies. We used the database of «Soils&rocks» block for necessary engineering calculations (slope stability, filled soil postcompaction, etc.). Having been conducted simultaneously, the work allowed us inserting in the GIS-model the information obtained in the course of the survey. As a result of engineering-geological survey aimed at 582 residential buildings, it was found out that exogenous geological processes influenced only 39 buildings, and 12 of them were subject to immediate resettlement.

3.6. *Updating engineering-geological conditions maps for development of Kazan territory*.
On the basis of the existing GIS-model after the preliminary transformation of vector themes from ESRI environment into MapInfo environment, as a part of preparation for the new General Plan of the city (it is planned to increase the city area to 2025) three new digital engineering geological maps were built: a seismic microzonation (1: 100 000) map, an engineering geological map (1: 25 000), and an aggregate map of the development complexity (1: 25 000). Spatial boundaries of the territory were extended while developing the maps. Engineering and geological conditions were detailed and updated taking into account new regulatory documents. Also, new thematic layers were added in the GIS-model, engineering-geological zoning was performed again, and recommendations on measures for land development were made. GenPlan Institute of Moscow is currently planning a new residential and commercial development taking into account the newly created GIS-model maps. A fragment of one map is shown in Figure 1.

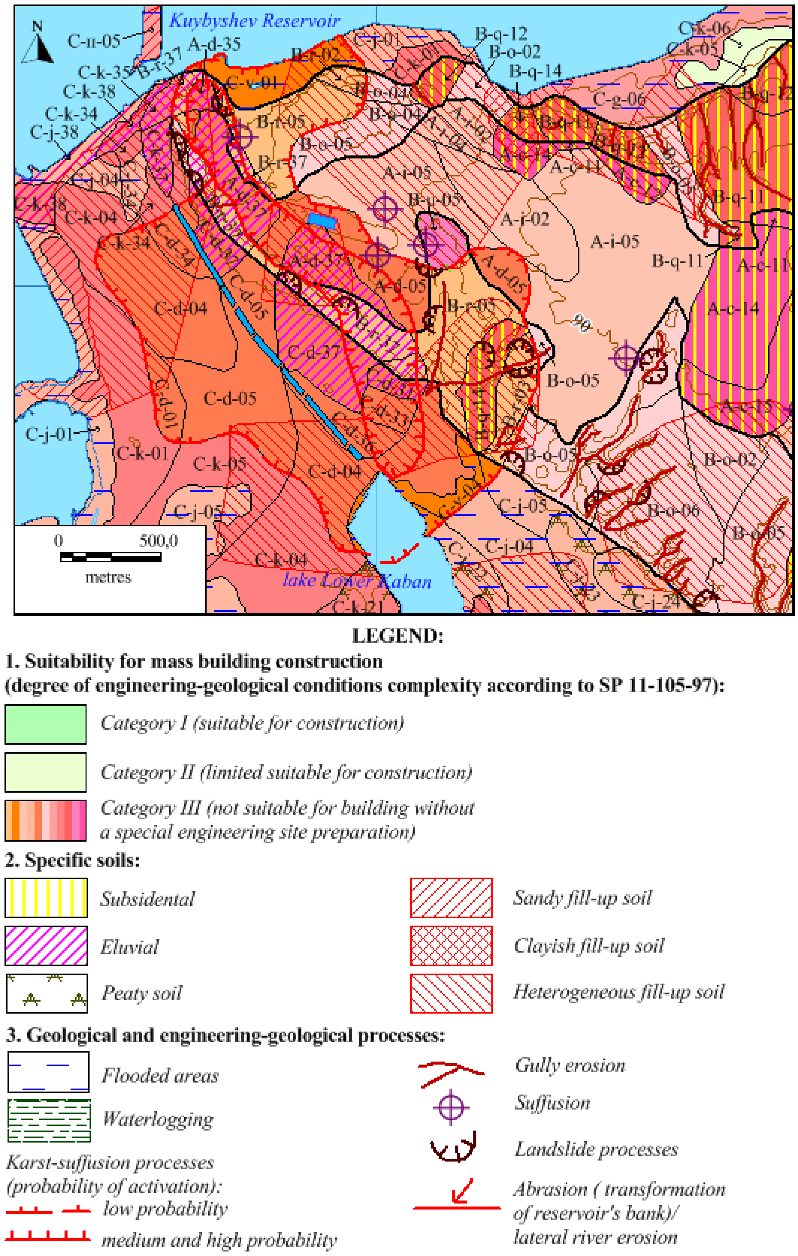

Figure 1. A fragment of an aggregate map of Kazan city development complexity. Indexes within polygons (e.g., C-j-05): A - watersheds (high terraces), B - slopes, C - lowlands (lower terraces); d, k, j and other uppercase letters of the alphabet - a certain set of exogenous geological processes; 01, 02, 03, and other two-digit numbers - the type of soil stratum.

4. Conclusion
The offered digital model of Kazan city geological environment meets the modern requirements for a complex model. This model has a structured database of Kazan hydrogeological and engineering-geological objects with the ability to search for, sort out, and analyze information. The possibility of hydrological conditions modeling and further forecasting, as well as convenient form of results

representation are present there. The above mentioned examples show that the offered model of the geological environment can be successfully used to solve various applied and scientific problems.

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