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Calculation of the stress-strain state of soil massifs with karst-suffusion cavities

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Abstract. For the North-Eastern part of the Kazan the problem of karst-suffusion danger is rather actual that is associated with the presence and occurrence close to the surface of carbonate eluvium. Currently in this area of the city is an active construction of various facilities.
This article is presented the results of calculation the parameters of the cavities and their spatial location on condition of that collapse of the soil massif is possible. The calculation model included the geometrical model of the engineering-geological section, supplemented by physical and mechanical properties as well as a cavity of cylindrical shape of different geometry. Earlier, the authors have completed and published studies to determine the critical diameter and critical depth of a cavity having the form of a simple cylinder. In reality the cavities have a more complex geometry so in this work the modelling was aimed at finding the critical parameters for different types of karst-suffusion cavities discovered in the study area.
The simulation results have allowed establishing that the danger of collapse of the soil above the cavity largely depends on its diameter and position in space. Several typical calculation cases were identified. For each case was the effect of the cavity on the redistribution of stresses in the soil massifs. It is possible to develop recommendations for the design of buildings and structures in the study area.
The research results showed good agreement with the results of field studies.

1. Introduction

Location: Eastern-European platform, left bank of the Volga River, valleys of small young rivers Noksa and Kinderka. The surface is horizontal and flat increasing in areas with erosion developing slopes is increasing. Geology: Permian carbonate and clastic rocks with almost horizontal bedding of the layers. Surface is often blurred. The upper layers of rocks are changed to soil (eluvium). They lie mainly on the alluvial soils of the Quaternary. Thickness is from a few ten meters to several centimeters. Ground water occurrence is at a depth of 10 m. The composition of the water is hydrocarbonate-calcium with mineralization up to 0.8 g/L [1].

Karst-suffusion processes are developing on the slopes of the rivers Kinderka and Noksa. Often the areas with the maximum number of sinkholes are erosive forms of non-permanent watercourses and

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major Pleistocene karst forms (the process in the present inactive) (Figure 1). All the sites can be divided into two types.

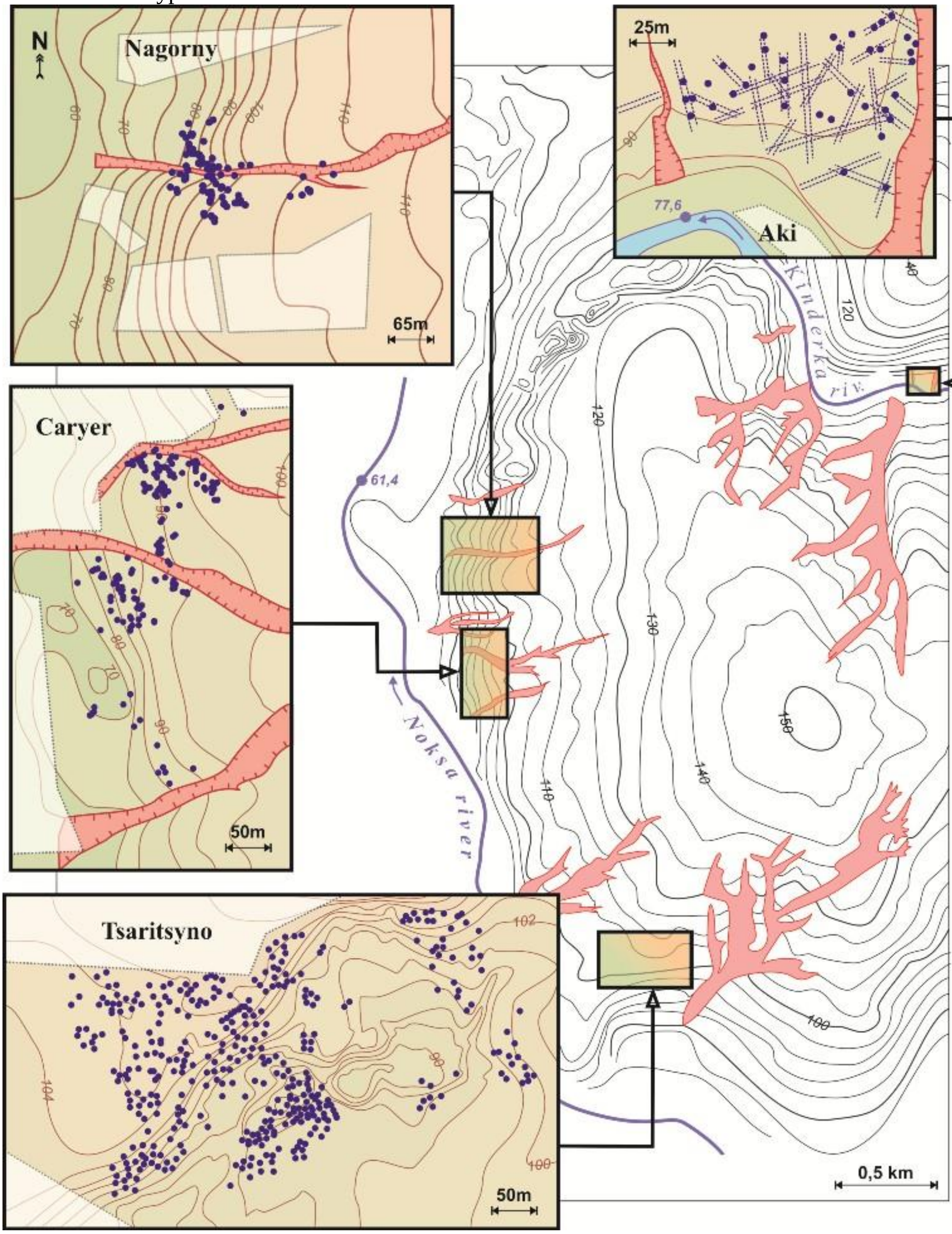

Figure 1. The areas of development of karst-suffusion processes in the North-East of Kazan city. The symbology: Pink color polygons with a red outline – erosion forms of non-permanent watercourses, purple point – sinkhole, double purple dotted lines – the furrow on the surface, the grey polygons with dashed contour - residential houses.

In the areas of the first type are observed typical failure sinkholes having round shape (diameter of not more than 10 m, often in the range of 2.5 – 6.0 m, maximum depth of 4.5 m, often from 1.0 to 2.5 m) [2]. Sinkholes are associated with suffusion inclined channels with a diameter of not more than 0.5 m (in some cases up to 1 m). Within the study area we selected three such sites with many sinkholes. Information on the number of sinkholes is given in Table 1.

Figure 2. The results of the activation of karst-suffusion processes in the area of Tsaritsyno. Left: a fresh failure in May 2016. In the centre: two-year sinkhole with the entrance to the suffusion channel in the bottom (dark spot in the center) (may 2016). Right: satellite image from Google April 4, 2013.

White spots are the sinkholes filled with snow.

On the single site of the second type is dominated by the furrows to a depth of not more than 1.5 m and width to 3 m. Sinkholes are also present. They are often located in the furrows. The groups of sinkholes in most cases form a straight chain. The diameter of the sinkholes doesn't exceed 4-5 m, often of 1.5 – 3.0 m, depth can reach 4-5 meters. Furrows and sinkholes are associated with systems of cracks in the carbonate rocks and with zones of dispersed decompressed eluvium. Sometimes cavities are present in such zones because the eluvium has taken out by the water of the aeration zone. Information of the number of sinkholes and furrows on this site is given in the Table 1.

Table 1. Characteristic of sites of active karst-suffusion processes

Name of the site	Square m^2	Type of massif to the depth of 30 m	The approximate number of sinkholes/furrows (2016)	The number of new sinkholes (in pieces to km^2) (since 2003)
Tsaritsyno*	89 402	dispersive soils prevail over rocks	386	149
Caryer	22514		87	1-2
Nagorny	13659		156	8
Aki	13125	rocks prevail over dispersive soils	37/29	138

* - more detailed information is presented in the work [1].

For modelling failures in soil was chosen two sites of different types with the biggest activity of karst-suffusion processes: sites of Tsaritsyno and of Aki.

Figure 3. Surface karst-suffusion forms on the site of Aki. Left: a linear furrow with a depth of 1.0 to 1.5 m, which intersect each other. Views to the South may 2011. Right: satellite image from Google may 25, 2012. In the Central part of the image see numerous furrows and sinkholes (dark spots with white outline on the North side).

1.1 Tsaritsyno site

The site is located in the South of the study area, on the right bank of the Noksa River. The development of karst-suffusion processes is caused the large (more than 30 m) thickness of carbonate eluvium (the ratio of calcite to dolomite varies from 1/1 to 1/10). It is the suffusion unstable soil due to low cohesion and large heterogeneity (history, position in the section and properties are detailed in [3]). As a result in alluvium channels have formed. They incipient deep down on the contact with a large zone of decompression and gradually grow up. At a certain thickness of the channel's covering soil failure happens with the appearance of a sinkhole on the surface. A large zone of decompression was discovered at a depth of 40-80m [4]. Also site has favorable conditions for the collection and infiltration of surface water and precipitation (type of covering soils – sand, sandy loam, clay loam).

The thickness of aeration zone of up to 30 m, therefore, there is a large water pressure gradient in the period of rains and snow melting.

An example of the geological structure of a part of the site is shown in Fig.4. Properties of carbonate eluvium is given in Table 2.

Table 2. Physical and mechanical properties of the carbonate eluvium

Physical properties	Solid particles density (g/cm^3)	Soil density (g/cm^3)	Dry soil density (g/cm^3)	Water content (%)	Void ratio	Liquid limit	Plastic limit	Plasticity index	Liquidity index	Degree of saturation
	ρ_s	ρ	ρ_d	W	e	W_L	W_p	I_p	I_L	S_r
Max	2.88	2.04	1.82	38.89	1.07	0.43	0.22	0.22	1.08	1.00
Min	2.63	1.84	1.32	5.62	0.49	0.19	0.08	0.09	-0.86	0.02
Mean	2.76	1.94	1.65	18.20	0.68	0.29	0.15	0.15	0.30	0.76

Mechanical properties		Natural water contant	Saturated state
Modulus of deformation (MPa) at P=0.1-0.2МПа	E_{mk}	32.0	31.8
Undrained shear strength (kPa)	c	26	20
Angle of friction (degree)	φ	24.8	20.1

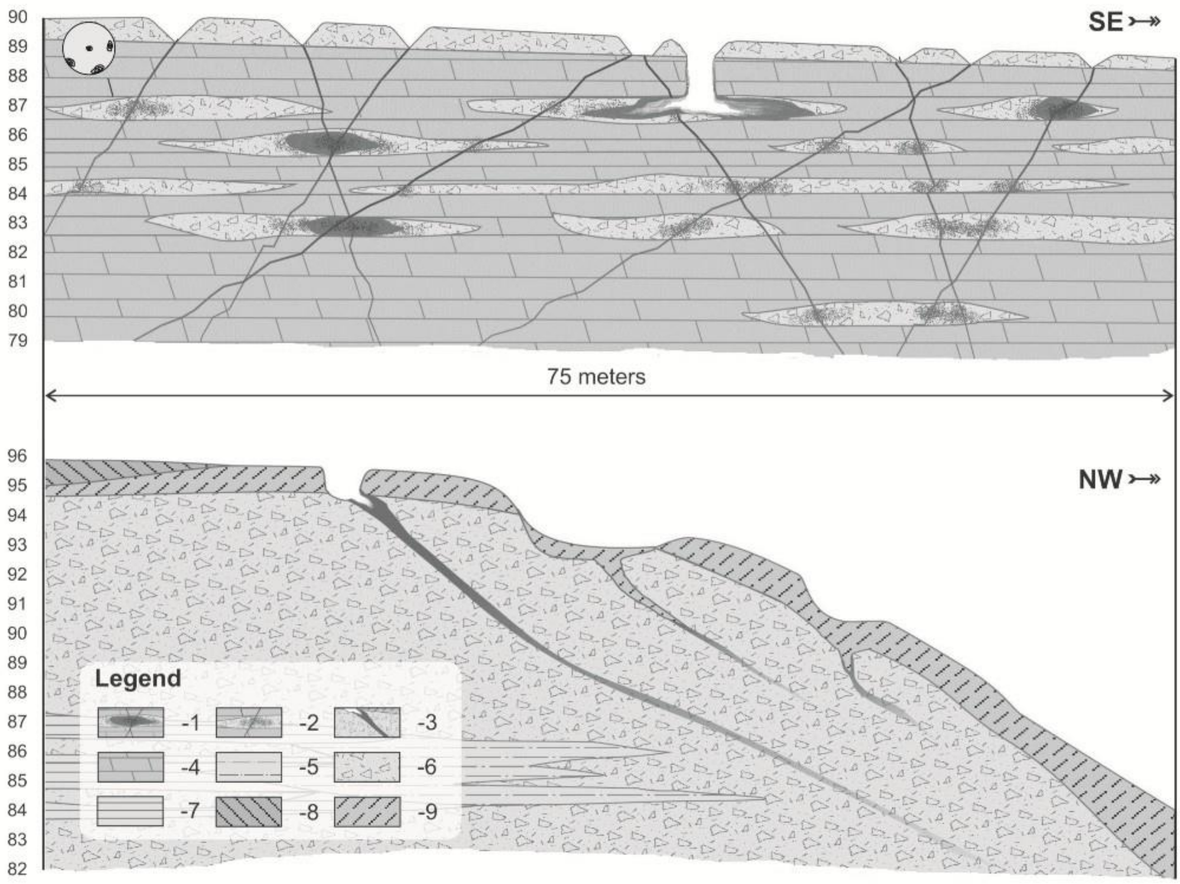

Figure 4. Examples of the geological conditions of the two types of karst-suffusion massifs (zone of aeration). Top: rock karst-suffusion massif of the site of Aki. Bottom: dispersive karst-suffusion massive of the site Tsaritsyno. Legend: 1 – cavities and large cracks, 2 – zone of decompression in the lenses and interlayers of carbonate eluvium, 3 – ponors in the thickness of eluvium, 4 – dolomites; 5 – siltstones, 6 – carbonate eluvium, 7 – clays, 8 – loams, 9 – sandy loams.

1.2 Aki site

The site is located in the North-East of the study area on the right steep Bank of the little river Kinderka (Figure1). Geology: the upper part - carbonate eluvium thickness not exceeding 1.5 m in composition and properties similar to the soils of the site Tsaritsyno. The rest of the part is composed of calcareous dolomites, locally altered to fine-grained soils (thin layers of lenses up to 1m). Pelitomorphic and fine-grained calcareous dolomites with inequigranular massive or lamellar structure contain calcite from 6 to 47%. They are characterized by heterogeneous porosity up to 15%. Half of the pores – ultrapores and micropores, the other half are large filamentous pores (Figure 5). Some of the dolomites have secondary silification, ferruginization, calcitization.

Properties of dolomite are given in Table 3

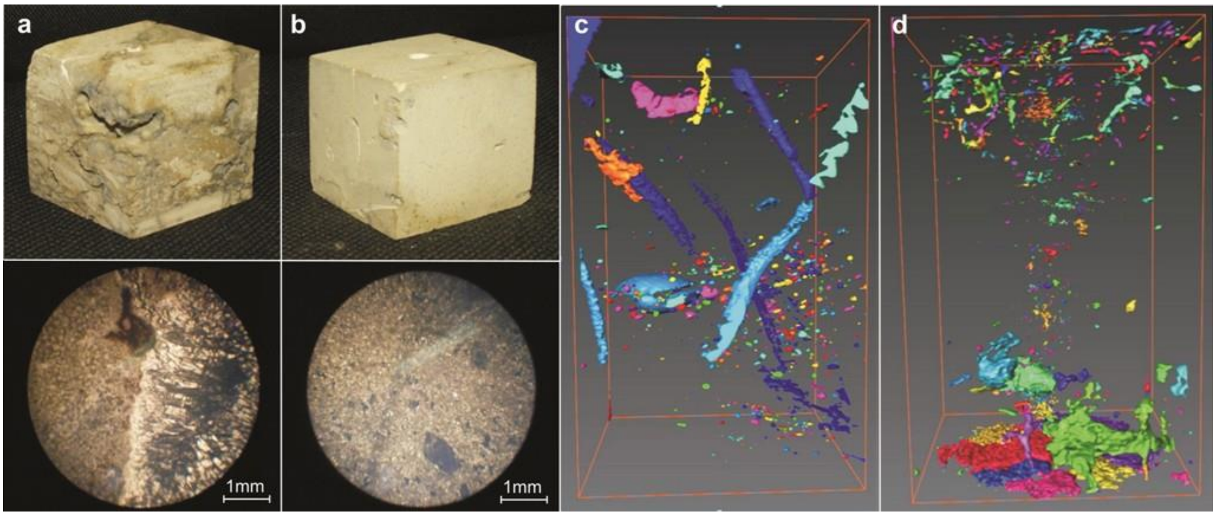

Figure 5. Porosity of Perm dolomites: heterogeneous by size, shape and position in space. Top left: samples of cubic shape with sides 4 cm. Bottom right: microstucture of dolomites under the microscope (×10). a – coefficient of porosity is 0.18 (mainly macropores), secondary calcitization and silification; b – coefficient of porosity is 0.51 (mainly mesopore). Right: Geometry of the pore space obtained using X-ray computed tomography on samples 4x4x7 cm.

Table 3. Physical and mechanical properties of the dolomites

	Solid particles density (g/cm^3)	Soil density(g/cm^3)	Void ratio	Elastic modulus (MPa)	Uniaxial compression strength (MPa)	Uniaxial tensile strength (MPa)
	ρ_s	ρ	e	E	R_c	R_r
Max	2.81	2.42	0.45	5860	44	4.4
Min	2.78	1.94	0.15	1542	13	1.5
Mean	2.79	2.19	0.28	3687	25	3.0

Thus the massif is characterized by lithologic heterogeneity as for stratification (primary, due to the peculiarities of sedimentation) and heterogeneity disagree with the stratification (secondary, caused postsedimentation changes such as silification, cavernosity, heterogeneous weathering).

The massif is broken by several systems of cracks. Their position is shown in Figure 4.

Such structure of the massif predetermined another type of formation of surface karst-suffusion forms of relief. By infiltration of snowmelt and rain water over the cracks in the thickness of the dispersive upper layer long furrows are formed [5]. Over the eluvium lays associated with cracks failures are formed. Sometimes eventually form multi-level cavity, the bottom part of which come out at the base of the slope [6].

2. Methods

The possibility of the formation of karst-suffusion cavities in the design of buildings and structures in the study area is relevant. And the most dangerous is the option, when the dimensions of the cavity reach a certain critical size, at which sudden loss of stability of the soil base can occur.

In this paper Plaxis Software was used to solve these problems. With Plaxis Software we can accurately model the karst-suffision process, by activating and deactivating soil clusters and structural elements in each calculation phase.

The calculation was performed for two settlement types shown in Figure 4. For the first type geological massif was presented as a dolomite rock, containing interlayers of carbonate eluvium. The dolomites were modeled using the model of the HOEK-BROWN, carbonate eluvium – with the help of the model of COULOMB-MOHR [7]. Properties of dolomite have been taken on the basis of Table 3. Cracks in the massif were modeled by interfaces. In the first phase of calculation was produced in the generation of the initial stresses in the soil mass. Then calculation was carried out in the mode of plastic calculation [8] with the appearance and gradual increase in the size of the cavity in the interlayer of eluvium (Figure 6). The desired value is the critical size of the cavity when destroy of the massif above the cavity is happening. That is the calculation is carried out on the strength of the rock massif.

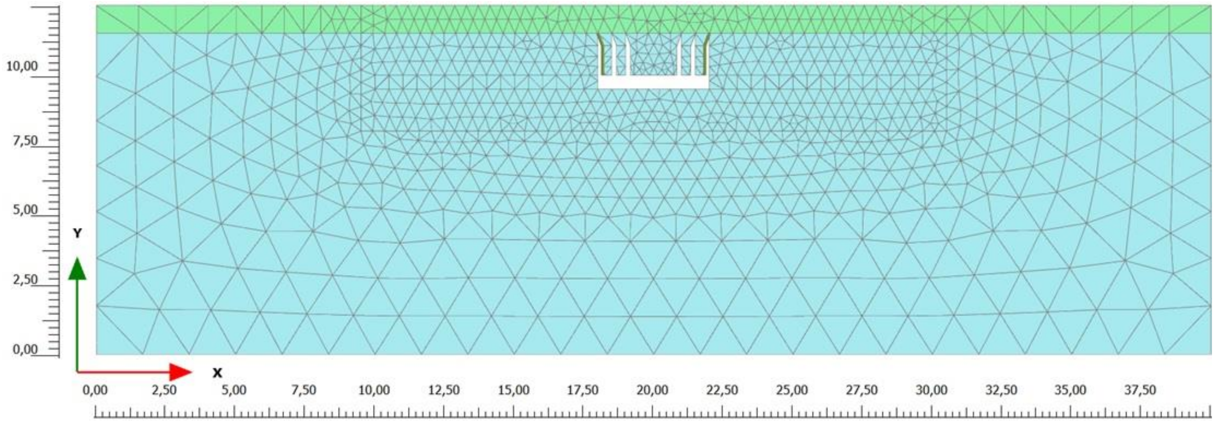

Figure 6. Calculation scheme of a cavity in a rock massif

The second type include massif of dispersive soil in which grows the inclined conical cavity (Figure 7). The calculate task is to find such a size of a cavity when the surface's subsidence reaches the value of 10 cm [9]. That is the calculation is carried out on the deformation of the dispersive massif. A value of 10 cm is taken as critical or highly significant for most buildings and structures [10].

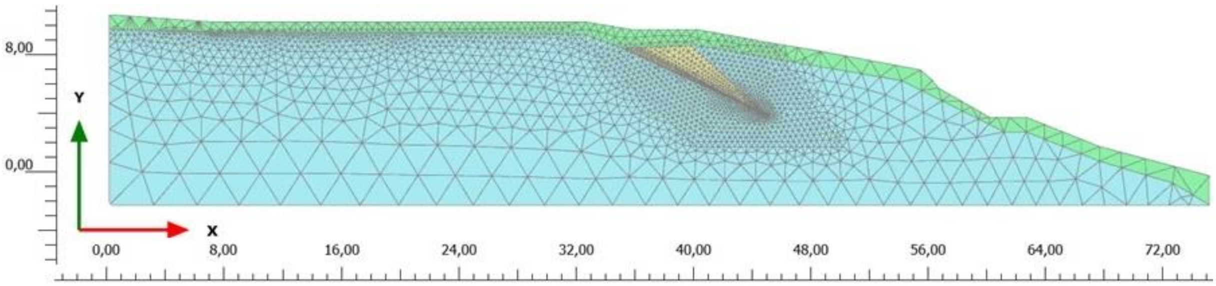

Figure 7. Calculation scheme of conical cavity in carbonate eluvium

3. Results and Discussion

The calculations are showing that for rock karst-suffusion massifs the critical cavity diameter is 4 m. At these values there is a sharp increase of stresses and strains in the massif above the cavity (Figure 8).

This value is very well correlated with the size of the sinkholes observed on the site of Aki [11]. This allows us to conclude that the reason for the appearance of surface karst-suffusion forms in the study area is suffusion removal of soil from layers of carbonate eluvium, accompanied by gravitational collapse of the soil massif above the cavity.

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The dispersive karst-suffusion massifs are often characterized the emergence of unacceptable subsidence on the ground’s surface. As a result of calculations it is established that under the assumed strength and deformation properties of carbonate eluvium displacement of the surface 10 cm is achieved when the size of the cavity in the upper part equal to 2 m.

In previously published work [12] it was shown that when the diameter of the cavity 2 m there is its sudden collapse, which not always coincides with the observed real processes. The cavity was modeled as a vertical cylinder. Modeling of the cavity in the form of an inclined cone (which is much closer to actually observed cavities in eluvium) shows that at these sizes the process can be accompanied not by sudden collapse and the appearance of the subsidence of the ground's surface. The nature of the manifestations on the surface of the growth process of underground cavities depends apparently from thickness and type of overlying layers. In the solved problem carbonate eluvium as close as possible lied to the ground surface and was covered with a slight layer of dispersive soil. As can be seen, in this case the growth of the cavity is accompanied by slow subsidence of ground's surface.

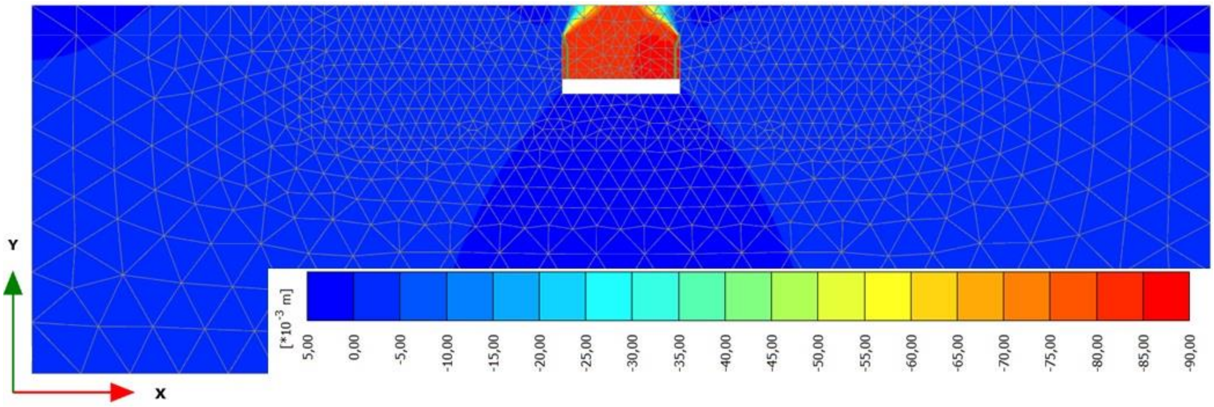

Figure 8. The isofields of vertical deformations of a rock massif with a cavity width of 4 m

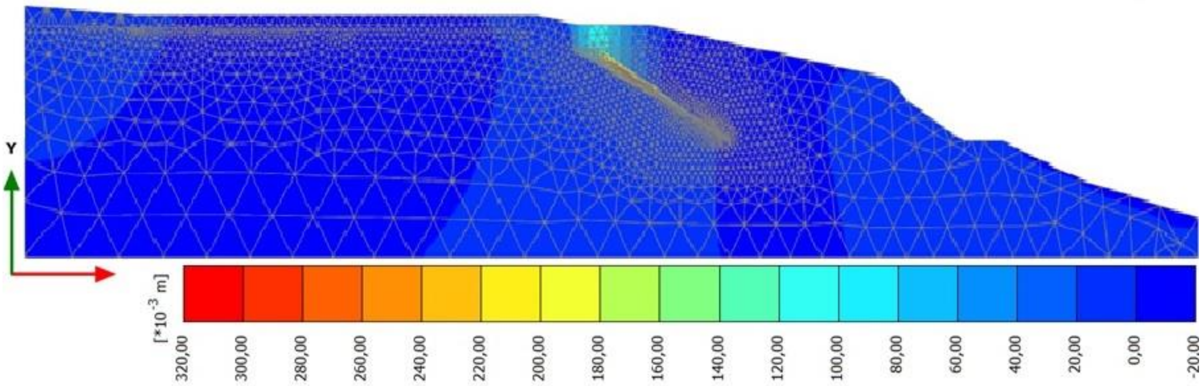

Figure 9. The isofields of vertical deformations of a dispersive massif with conical cavity

4. Conclusions

- The nature of karst-suffusion processes which is shown in the North-East of the city of Kazan depends on the geological structure of rock and soil and can be subdivided into two specific types.

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- Dimensions of critical cavities can be calculated using Plaxis Software with good accuracy.
- For rock karst-suffusion massifs in the study area critical diameter underground cavity is to 4 m.
- For dispersive karst-suffusion massifs the emergence and growth of the cavity can cause a slow subsidence of the surface. The value of subsidence of the ground's surface to 10 cm is achieved when the diameter of the cavity in the upper part of 2 m.
- The results have good agreement with the results of field observations.

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