Destruction of aquitards, sinkhole development and land subsidence in Moscow

ALEXANDER V. ANIKEEV[1]

[1] *Institute of Environmental Geoscience RAS. (e-mail: anikeev_alex@mail.ru)*

Abstract: Experiments are described which detail the process of spalling and fissuring of clay layers over a weakened zone such as a karst cave, cavity or open-joint fissure. The process, here named casual hydrofracturing, starts in weakly permeable, water-saturated rocks under a critical drop of aquifer head. Almost instantly the rupture front propagates from the bed base to the equilibrium state surface. The spalling results in the collapse of relatively thin confining beds and the entrainment of any overlying unbound soils into a fissure or karst void. Arch-like cavities and ellipse-like regions of disturbed clay form within thick weakly permeable strata. Developing in the vicinity of numerous fractures and caverns, the hydrofracturing forms in the contact interbeds where clay has different characteristics to the underlying rock. The strain and stress characteristics of the disturbed interbeds are much smaller than those of the undisturbed ones.

This process generates sinkholes and land subsidence within urban territories where the natural groundwater regime is strongly impacted by anthropogenic uses. For example, the engineering geological conditions of the north-west area of Moscow city have changed as a result of long-term pumping from the Carboniferous confined aquifers. These effects are discussed with results of the calculated stabilities of the Jurassic and Carboniferous aquitards. Both field observations and calculations testify to the partial or complete disturbance of the clay cover in this area. This is the main cause of sinkhole formation in the north slope zone of the pre-glacial Moscow river valley. It is also the cause of anomalously deep subsidence in its central part. If it is carried out before changing the hydrological environment, such an analysis may be useful for groundwater monitoring and as a tool to forecast hazardous geological processes in urban areas.

Résumé: On analyse le processus de destruction de la couche argileuse au-dessus de la partie faible du massif des formations solubles (embut, alvéole, fracture ouverte, etc.) découvert dans les épreuves et dénommé comme la fracturation hydraulique accidentelle de la couche. Elle prend naissance dans les sols saturés d'eau peu perméables à la réduction critique de la charge des eaux fissurées et karstiques. Presque instantanément le front de cassement monte du soubassement de la couche jusqu'à la surface de tension extrême. Le processus finit par la tombée des couches imperméables relativement minces et par l'entrée des sols inconsistants surimposés dans l'espace fissuré et poreux des formations solubles. Dans les couches épaisses peu perméables se forment les cavités arquées et zones elliptiques des argiles détruites. Ce processus se développant près de nombreuses zones faibles (les zones de la fissurité et cavitation élevée) cause la formation des bancs intermédiaires de contacts ayant les caractéristiques de déformation et de résistance beaucoup plus basses que les caractéristiques des argiles non-détruites.

Le processus analysé est à l'origine de la formation des entonnoirs karstiques de suffosion et la dépression du sol dans les nombreux territoires urbains où il y a un grand change technogène des conditions naturelles des eaux souterraines. A titre exemplatif on analyse les conditions géotechniques du district nord-ouest de Moscou, leur change à la suite de long épuisement des eaux carbonifères et les sorties de l'estimation de résistance des couches imperméables jurassiques et carbonifères. Tant les essais en situ que les sorties des calculs montrent la destruction complète ou partielle des couches argileuses dans ce district, ce qui constitue une des causes principales pour la formation des entonnoirs d'effondrement dans le bord du nord de la vallée préglaciaire de la rivière Moskva et pour anomalement grande dépression du sol dans sa partie centrale. Une telle analyse exécutée avant la détérioration des conditions hydrogéologiques peut se rendre utile pour la prédiction du développement des processus géologiques dangereux sur les territoires urbanisés.

Keywords: caverns, hydraulic fracturing, land subsidence, overburden stability, pore pressure, stress

INTRODUCTION

Land subsidence and especially sinkholes induced by ground water withdrawal in mantled karst terrains, are serious geological hazards (ASCE 2003, PSU 2004). These cause human misery and damage to buildings and engineering structures. Such damage causes difficulties for urban planning, construction and management. At present, the local prediction of sinkhole-subsidence development is far from perfect. One of the reasons is the disregard of the real collapse mechanisms when evaluating the stability of the karst overburden. There are two fundamentally important problems in such evaluations. The first concerns the study of the disturbance of sand deposits by piping or suffosion processes. This subject is not within the scope of this study, but has been considered by other investigators (Anikeev & Fomenko 1995, Anikeev & Kolomensky 2002). The second relates to the destruction of the weakly permeable, mostly, clayey strata which serve as isolating layers protecting the karst aquifers from contaminated surface water and preventing the transport of water saturated sands into karst cavities and fissure voids.

The failure process described in this paper was suggested by Anikeev (1991, 1993, 1999), Sheng & Helm (1995) and Tharp (1999, 2002, 2003) who noted that high pore pressure gradients at the perimeter of a soil void could lead to failure by hydraulic fracturing. Over the past eighteen years experiments by Anikeev (1991) showed that a sudden decline of water head in a confined aquifer caused the fracturing of a confining layer above even a small rock cavity (Figure 1). Sloughing and crumbling of water-saturated clays are observed to form inside an arch-shaped zone. The rupture front propagates upward with great speed from the bed floor to the interface where stress is in a state of equilibrium (Figure 1, a). This causes relatively thin weakly permeable beds to cave in (Anikeev 1993). This process has been named casual hydrofracturing (Anikeev 1991) to emphasize the difference between it and that of premeditated rock disintegration induced by fluid injection into boreholes or mines. Sheng & Helm (1995) noted that during or after a rainstorm a sudden increase of pore water pressure in a subsurface crack would lead to its propagation and development into fissures at the land surface. It also results from the difference in hydraulic diffusivities of the void and the surrounding soil, which keeps the water pressure inside a void from dissipating quickly into a rock massif. Using finite element modelling, Tharp (1999) found that if the soil is elastic, even very high pore pressure gradients do not produce hydraulic fractures. A poroelastic analysis of transient pore pressure distribution predicts failure for reasonable drawdowns, but only if soil permeability is much lower than that of most soils where sinkholes develop (Tharp 2002). Elastic-plastic modelling with such pore pressure indicates that the first hydraulic fracture is followed by a rapid succession of fractures that will propagate the spherical soil void to near the ground surface. It is significant that for spherical symmetry in all boundary conditions, the head drop necessary to produce sinkholes is independent of soil thickness for a certain range of soil cohesion and thickness, and nearly independent of the size of the initial void for steady state or near steady state pore pressure conditions (Tharp 2003). It is showed below that these conclusions are strongly restricted to the real form of a rock or soil cavern and therefore to the stress state of the soils in the vicinity of an opening.

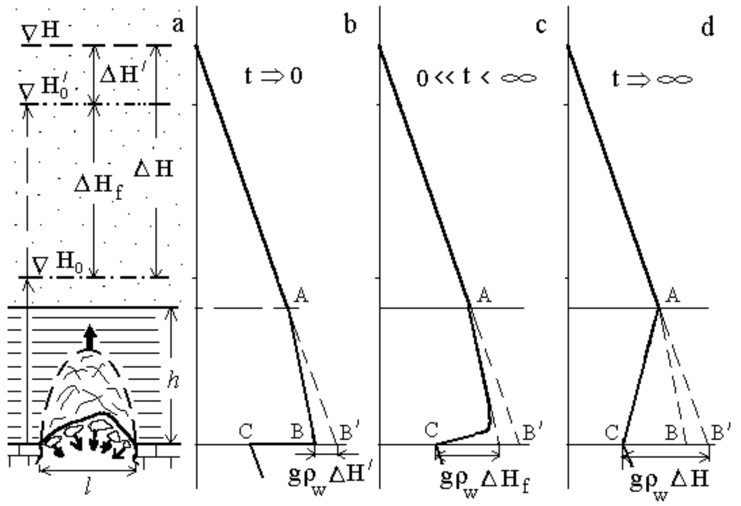

Figure 1. Mechanism of hydraulic fracturing (a), and pore pressure diagrams at the initial moment (b), intermediate stage of downward seepage (c) and final one (d). ∇H: water-table (the level of unconfined water); $\nabla H'_0$ and ∇H_0: potentiometric level of karst water before and after water head decline; *l*: the span of a cavern (rock void) at the base of karst overburden; *h*: the thickness of confining bed; t: time. Big arrow and small ones show respectively the propagation of crumbling front and the "shooting" of clay spalls and pieces from the roof of soil void.

HYDRAULIC FRACTURING OVER KARST VOID

Geomechanical analysis

The driving force, which triggers the hydraulic fracturing of a confining stratum, is excess hydrostatic pressure developing in soil pores due to the head drop in the underlying confined aquifer. There are three main conditions for failure:

- The presence of a weakened zone (karst cave, cavity, open-joint fissure, etc.)
- The great difference in hydraulic conductivities of confining layer and aquifer
- $w \geq 85e\rho_w/\rho > w_m$; where w and w_m are moisture content and soil moisture in p.c., ρ_w and ρ are water density and density of mineral portion, e is porosity coefficient of clay soil

Generally, the pore water pressure inside the confining layer consists of two parts:

$$u = \gamma_w \Delta H = K_\sigma \sigma_w + K_\tau \tau_w \qquad (1)$$

where $\gamma_w \approx 10^4$ N/m^3 is the unit weight of water, ΔH is the magnitude of water head decline in m, K_σ and K_τ are coefficients ($K_\sigma + K_\tau = 1$), σ_w are the stresses in pore water normal to soil particles, or excess hydrostatic pressure in kPa; τ_w are the seepage stresses tangential to the surface of soil grains, hydrodynamic pressure or effective stresses in the theory of aquifer-system compaction in kPa (Terzaghi & Peck. 1967; Poland. 1981). Commonly, the value of K_σ/K_τ is the function of time, head drop and hydraulic diffusivity of soil. Accordingly to the second failure condition we can suppose that $K_\sigma/K_\tau >> 1$ independent of non-steady state, or steady state percolation. Then equation (1) is rewritten as follows:

$$u = \sigma_w = \gamma_w \Delta H \qquad (2)$$

In the vicinity of a karst void not balanced by grain-to-grain pressure, the excess hydrostatic stresses cause tensile failure of a confining bed long before the dynamic seepage stresses will be exerted on the grains by the viscous drag of vertically moving interstitial water (Figure 1, d). The hydraulic fracturing will occur, if the tensile strength σ_t assumed to be the same in principal stress directions is

$$\sigma_t \leq \sigma - \sigma_w \qquad (3)$$

where $\sigma = \sigma_{1, 2, 3}$ are principal normal stresses in solid clay above an opening in kPa. For simplicity, we shall assume that $\sigma_t = c$, where c is cohesion in kPa. Otherwise, the utilization of failure criterion (3) presents some difficulties in practice, especially for plastic soils. Using equations (2) and (3) one can obtain the failure or critical value of water head decline:

$$\Delta H_f = (c + \sigma)/\gamma_w \qquad (4)$$

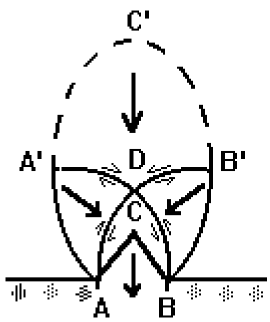

Figure 2. Region of influence of opening AB in the rigid base of a soil mass. ACB: falling block or cave-in zone; ADB: relieved arch or zone of dilatancy and potential cave-in; AA'D and BB'D: plastic wedges or zone of bearing pressure and potential slippage; DA'C B : zone of transit from anomalously high and low stresses to geostatic ones (zone of possible extrusion of fissured solid by downward water flow). Big arrows and small ones show the directions of potential soil flow and those of maximal tangential stresses.

The next obstacle concerns the identification of the stress state of a confining bed in the vicinity of an opening, which is usually of unknown dimensions. Figure 2 shows that a relieved arch ADB forms in soil overburden over a weakened zone. At the base of the arch stresses can even be tensile ($\sigma_{2,\,3} < 0$, $\sigma_1 = 0$). Near its top they are compressive ($\sigma_{1, 2, 3} > 0$) but they are small in terms of absolute value. In the first assumption we consider them to be equal to zero inside the zone of low stresses. In other words, we assume that the pressure of overlying rocks acts on wedges AA'D, BB'D (Figure 2), and because of soil cohesion, block ADB is hanging over the opening. Taking into account this assumption ($\sigma = \sigma_{1, 2, 3} = 0$) we obtain the simplest relationship between the failure value of water head decline ΔH_f and the standard engineering-geological characteristic of disperse rock c from expression (4):

$$\Delta H_f = c/\gamma_w \qquad (5)$$

Considering the scheme for the instantaneous propagation of the rupture front from the bed floor to the roof under a drop in head of H_0' to H_0 (Figure 1, a). Being fissured, a clay stratum will be affected by the downward flow of water, and the head difference will wholly manifest itself in the seepage stresses $u = \gamma_w\Delta H = \tau_w$, $K_\sigma/K_\tau << 1$ (Figure 1, d). Before the fracturing, in comparison with water pressure at the top of underlying rock, the excess hydrostatic pressure $(\sigma_w)_z$ remains constant or changes inside a confining bed (Figure 3). If the hydraulic gradient at the initial stage of steady state percolation $I = \Delta H'/h \geq 1$ (Figure 3, b, c), then the value of critical head drop at the bed floor is evidently determined by expression (5): $\Delta H_0 = \Delta H_f$, $\Delta H_h \geq \Delta H_f$. For $I < 1$, $(\sigma_w)_z$ diminishes from $CB = \Delta H_0$ to $DA = \Delta H_h$ as the unit weight of water is assumed to be unity, and the pressure is expressed in terms of the height of an equivalent column of water (Figure 3, a). Then, as shown in Figure 3,

$$\Delta H_z = \Delta H_0 - z + Iz \qquad (6)$$

where z is a height above the bed floor in m. Substituting $\Delta H_z = \Delta H_h = c/\gamma_w$, $z = h$ and $\Delta H_0 = \Delta H_f$ into (6) we obtain

$$\Delta H_f = c/\gamma_w + h(1 - I), \qquad (7)$$

where h is the thickness of a confining bed in m. Thus, if $I \geq 1$, the condition (5) is more than sufficient for the bed to be fractured from the floor to the roof. If $0 < I < 1$, $\Delta H_0 < c/\gamma_w + h$, and in the case of upward initial filtration where

$I < 0$, $\Delta H_0 > c/\gamma_w + h$. In the peculiar but widespread case of initial hydrostatic conditions $I = 0$ ($H \approx H_0'$ in Figure 1) the process will start at the layer floor under condition (5), and a confining layer will be entirely disturbed under condition (7a):

$$\Delta H_f = c/\gamma_w + h \qquad (7a)$$

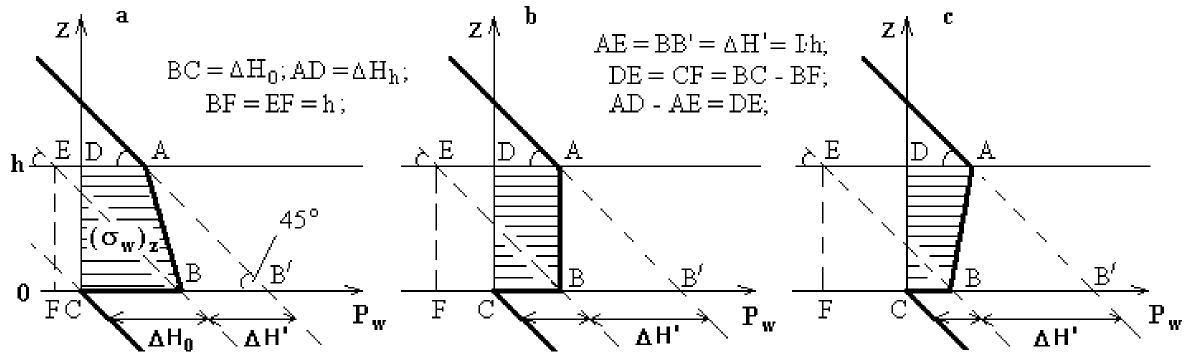

Figure 3. Scheme to determine the critical value of excess pore pressure $(\sigma_w)_z$ at the floor of a confining bed with thickness h under a sudden decline of water head ΔH_0 in confined aquifer for $I = \Delta H'/h < 1$ (a), $I = 1$ (b) and $I > 1$ (c); P_w: water pressure, in meters of water column.

Thick bed failure in tests and some consequences

In the mid 1990's, the fracturing of thick confining beds was studied in various models for different water-saturated materials in numerous configurations (Anikeev, 1999). The technology of the tests and the theoretical foundation for modelling are not within the scope of this current paper. However, it should be noted that the experiments measured the alteration of water pressure beneath two- and three-layer models and recorded the induced processes. The results obtained (Figures 4 and 5) added some corrections to the presented concept.

It was found that hydraulic fracturing starts, but quickly finishes under the values of water head decrease (ΔH_{ex}) being 2,5 - 3 times smaller than those (ΔH_f) obtained from equations (5), (7). Under these conditions small three-cornered or box-shaped cavities form at the bed bottom (Figure 4). Where $\Delta H_f/\Delta H_{ex} = 1,5 - 2$, the process leads to the collapse of thin confining beds (h/l < 1,5). In the thick ones (h/l > 1,5-2,5) it results in an arch-like cavity with the height approximately equal to the opening span (l) in the rigid base (Fig. 4, 5, a). Besides, nearby and above zone ADB (Figure 2) clay cohesion may be partially disturbed, and the bed is somewhat crumbled. This is because further descent of water head pressure causes the downward movement or extrusion of the disintegrated clays in a way similar to that in which unbound soil flows through apertures. These magnitudes of ΔH_{ex} are between those of ΔH_f. At the beginning, the region of extrusion is like a vase (Figure 4), which probably results from the influence of compressed wedges (ADA', BOB' in Figure 2). Then it becomes wider and parabolic (Figure 4) or in thicker layers it becomes ellipsoidal (Figure 5, a). The crumbling and extrusion of soil inside the ellipsoid is accompanied by the cave-in of the upper portions and roof bending (Figure 5, a). The height of the ellipsoidal zone of extrusion coincides with the region of the influence (AA'C'B'B in Figure 2) and is five to seven times as large as the span. If $\Delta H_{ex} > \Delta H_f$, the extrusion continues, the bending increases, new fractures appear, and the old ones dilate or close (Fig. 5, b). It's possible to make an opening in a thick confining bed (5 in Figure 5), but that requires $\Delta H_{ex} >> \Delta H_f$.

From this, it is shown that there is good correspondence between the results of physical model tests and those of the calculations. As stated above, after the fissuring the excess hydrostatic stresses transform to the seepage ones, i.e. the transition $K_\sigma/K_\tau >> 1 \rightarrow K_\sigma/K_\tau << 1$ takes place in equation (1). Probably, that is why, an increase of the water head difference ($\Delta H_{ex} >> \Delta H_f$) is necessary to form a hole in thick aquitards. The discrepancy between ΔH_{ex} and ΔH_f at the beginning of the fracturing may be explained by the first assumption ($\sigma_t = c$). In reality the tensile strength of every rock is much smaller than its cohesion. The experiments testify to the correctness of the second assumption ($\sigma = \sigma_{1,2,3} = 0$) only for the zone of low stresses. Over the relieved arch the compressive stresses prevent the upward propagation of the spalling front in the form of macroscopic fissuring. Nevertheless, the disturbance of clay cohesion, the partial crumbling and changing of bound soils occur inside the large region near a weakened zone. The confined aquifers composed of soluble rocks such as limestone, dolomite, etc. are usually fissured and karstified. Developing in the vicinity of many fractures, caverns and caves, hydraulic fracturing can generate in the contact interbeds where impermeable rock is qualitatively distinguished from the original one (Fig. 6). The strain and stress characteristics of such interbeds are much smaller than that of the undisturbed soils. This can be the cause of extremely high compressibility of the clayey strata and land subsidence.

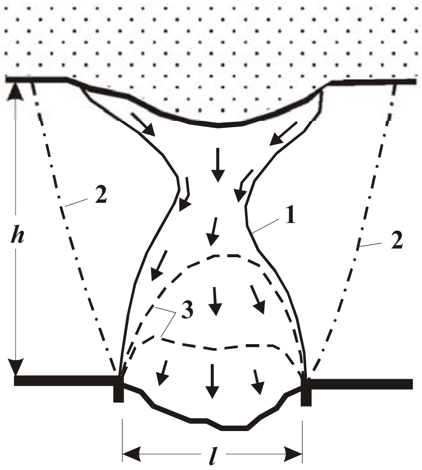

Figure 4. Extrusion zone (1) in the Upper Carboniferous and Upper Jurassic clays joined in a single stratum (h/l = 1,6) in the area of Tukhachevsky street in Moscow city (the results of physical model tests); 2 and 3: boundaries of open hole and soil cavity at the final and initial stages of fracturing, respectively. Arrows show the flow direction of crumbled clay solid.

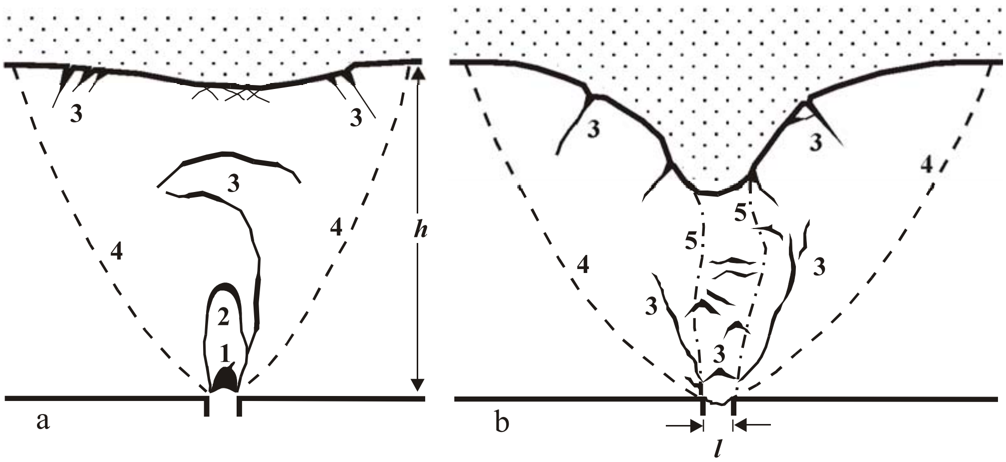

Figure 5. Modeling failure of the Upper Permian clay bed (h/l = 13,5) in an area of Dzerzhinsk city (Russia) at the initial-middle (a) and final (b) stages of hydraulic fracturing; 1: soil cavity; 2: zone of clay extrusion; 3: breakdown fractures; 4 and 5: boundaries of visible deformation and open hole, respectively.

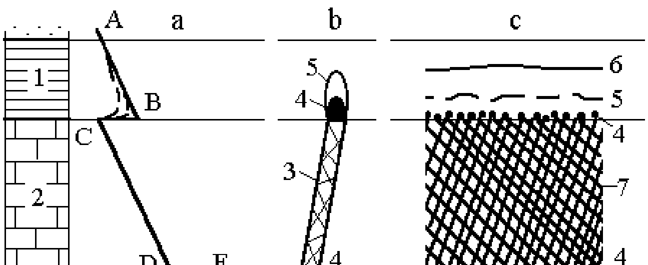

Figure 6. Conceptual model of weak interbed formation (c) under water head reduction (a); 1: confining bed and aquitard; 2: confined aquifer; 3: a single fissure; 4: soil voids; 5: zones of crumbling and extrusion; 6: boundaries of weak interbeds; 7: fissure system; ABCDEF: fluid pressure diagram.

INDUCED SINKHOLES AND LAND SUBSIDENCE IN THE NORTH-WEST REGION OF MOSCOW CITY

The north-west district of Moscow city is unfortunately known as the region of man-made sinkholes and land subsidence. The subsidence is commonly connected with karst and suffosion (piping), which develop in the north-slope zone of the pre-glacial Moscow river valley. In some places, subsidence development cannot be explained from the engineering geology point of view. Such an area of anomalously high land subsidence (with the average movement of 2,5 – 4 mm/year over an area 3,5 km long and 1,5 km wide) is situated along the 1-st Magistralnaya street (Osipov & Medvedev (eds), 1997); this coincides with the central part of the pre-Quaternary river entrenchment.

Site geology, engineering geology and hydrogeology

In this area the geology comprises a loose covering of Quaternary strata, 20 - 25 m thick, over a basement of Mesozoic and Palaeozoic strata (Figure 7). From the top to the bottom, the Quaternary sediments are represented by the Holocene anthropogenic deposits (thIV) and alluvial silt, sand, loam and clay of the river flat (aIV), the Upper Pleistocene alluvial sand of the second terrace (aIII), the Middle Pleistocene alluvial sand of the third terrace (aII) and glacial loam and clay loam (gII), the Lower-Middle Pleistocene fluvioglacial sand and limnoglacial loamy sand (l,f,gI-II). The Quaternary deposits overlap the Upper Jurassic clays (J_3cl), 1 – 3,5 m thick, the Upper Carboniferous strata and the undivided Upper and Middle Carboniferous limestones and dolomites (C_2mc-C_3sv) lying bellow. The Upper Carboniferous deposits are represented by the limestones of the Perkhurovskaya (C_3pr) and Ratmirovskaya (C_3rt) formations with a thickness of between 5 m and 7,5 m, the clays of the Neverovskaya Formation. (C_3nv) with a maximum thickness of 5 – 6 m and the Voskresenskaya Formation. (C_3vs), 8 to 11 m thick. In the bottom of pre-glacial valley the Upper Jurassic and Upper Carboniferous rocks are generally eroded except for the clays of the Voskresenskaya Formation. The Upper Jurassic clays have only been preserved at the north of the area (Figure 7).

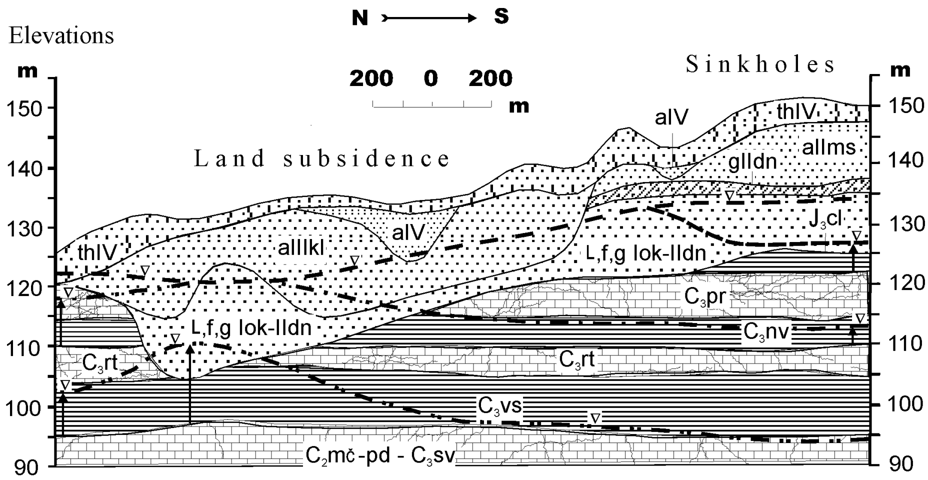

Figure 7. Hydrogeological cross-section through the rock massif; thIV, aIV: the Holocene anthropogenic deposits and alluvial sediments of the flood land; aIIIkl: the Upper Pleistocene alluvial sediments of the second stream terrace; aII, gII: the Middle Pleistocene alluvial sand of the third terrace and glacial clay loam; l,f,gI-II: the Lower-Middle Pleistocene fluvioglacial sand and limnoglacial loamy sand; J_3cl: the Upper Jurassic clays; C_3pr, C_3rt, C_3nv, C_3vs: the Upper Carboniferous carbonate rocks of the Perkhurovskaya and Ratmirovskaya Formations and clay rocks of the Neverovskaya and Voskresenskaya Formations; C_2mc-C_3sv: of the Upper and Middle Carboniferous limestones and dolomites; dotted lines and arrows show water table and piesometric levels. piesometric

The Upper Jurassic undisturbed clays are usually semihard-plastic and characterized by bulk density ρ_s = 1,31 – 1,67 g/cm^3, moisture content w = 0,28 – 0,34 and cohesion c = (1,26 – 1,91)·10^5 Pa. Induced sinkholes, 5 – 70 m in length and 0,5 – 2 m in depth, coincide with the area of thin Jurassic clay and over the last sixty years have developed widely on the north slope zone of pre-glacial river valley. The Upper Carboniferous clay rocks are characterized by the follow properties: ρ_s = 1,72 – 1,89 g/cm^3, w = 0,15 – 0,23, c = (1,8 – 3,2)·10^5 Pa near the pre-Quaternary basin divide and ρ_s = 1,35 – 1,60 g/cm^3, w = 0,34 – 0,44, c = (0,4 – 0,8)·10^5 Pa in the central part of the entrenchment. Strongly fractured and karstified, the Upper Carboniferous carbonate rocks are composed of blocks and fragments with sand and clay filler. The rock porosity is high (n = 0,23 – 0,48) and the fissure permeability characterized by hydraulic conductivity coefficient (k) varies from k = 0,041 cm/s (the Perkhurovskaya Formation.) to k = 0,023 cm/s (the Ratmirovskaya Formation.). Fissured and karstified, the Upper-Middle Carboniferous rocks (n = 0,21 – 0,32, k = 0,017 – 0,025) have some holes filled with residual colmatage formations of Paleozoic age. The traces of recent karst and large caves have not been encountered.

The upper unconfined aquifer, 10 – 15 m thick, is present within the Quaternary sands. The water table lies at the elevations of 120 – 135 m (Figure 7). The Upper Jurassic and Upper Carboniferous clay strata serve as aquitards for the surficial water in the north slope of the valley, and they are the confining beds for the first and second semiconfined aquifers formed by the limestones of the Perkhurovskaya and Ratmirovskaya formations (Figure 7). The piesometric level of the former is 5 – 7 m lower than the water table at the north of the region and that of the latter is 14 – 21 m lower. These aquifers unite and form the single unconfined aquifer near the bottom of the buried valley. The confined aquifer is found within the Upper-Middle Carboniferous carbonate deposits. The clays of the Voskresenskaya Formation function as a major separator dividing the ground and semi-confined waters from the confined one (Figure 7). The piesometric level of the last is 10 – 40 m lower than the groundwater table. At the beginning of the twentieth century all levels and the water table were at the same elevations of about 130 m. The long-continued karst water withdrawal has resulted in the decline of the piesometric levels by tens of meters. By the mid 1980's, the difference in elevations between the water table and the water heads was equal to at least 15 – 20 m, 20 – 25 m and 25 – 30 m respectively in the aquifers of the Perkhurovskaya and Ratmirovskaya formations and the Upper-Middle Carboniferous aquifer. Since the 1980's the karst water uptake has decreased and the water levels have been re-establishing.

Calculation results

Formulae (5) and (7a) have been utilized retrospectively to estimate the possibility of confining bed failure. As noted above, the tensile strength of every rock is much smaller than its cohesion. Because we do not exactly know the transient head differences, the following minimal values of the cohesion and water head decline were assumed with the following actual thicknesses i.e. the Jurassic clay: $c^J = 1{,}26 \cdot 10^5$ N/m^2, $h^J = 1 – 3{,}5$ m; the Upper Carboniferous clay strata: $c^{N,V} = 1{,}8 \cdot 10^5$ N/m^2, $h^N = 3 – 6$ m, $h^V = 8 – 11$ m; the Carboniferous aquifers: $\Delta H^P = 15$ m, $\Delta H^R = 20$ m, $\Delta H^C = 25$ m.

According to the values of cohesion we obtain from (5), we find that hydraulic fracturing started in the Jurassic layer and then the Upper Carboniferous when the values of water head decrease were $(\Delta H^P)_f = 12{,}6$ m and $(\Delta H^{R,C})_f = 18$ m respectively. In accordance with (7a) we can state that the values necessary for the Jurassic strata and those of the Perkhurovskaya and Ratmirovskaya formations to be fractured from the floor to the roof are: $(\Delta H^P)_f = 13{,}6 – 16{,}1$ m, $(\Delta H^R)_f = 21{,}0 – 24{,}0$ m and $(\Delta H^C)_f = 26{,}0 – 29{,}0$ m. Comparing these failure values of karst-water head decline with the observed ones of 15, 20 and 25 m, we see that all weakly permeable rocks in the region have been exposed to hydraulic fracturing. The Jurassic confining beds have been entirely ruptured where their thickness $h^J <$ 2,4 m. The observed values of 20 and 25 m are somewhat smaller for failures developed in the Upper Carboniferous strata and suggest that it must have already be partially disturbed. This answers why in the early 1980's the author observed, but could not explain, the local changes in the clay consistency and thickness in the area. Then it was found that the Upper Carboniferous clays of the north-west region were plastic and even soft plastic, easily folded by hand and why refolded folds were seen at some sites. The relatively large thickness of these beds and the absence of large karst voids have prevented the downward movement of the disintegrated clays and overlying sands; for this reason, we find no sinkholes in the central part of the region. However, the partial failure and the alteration of the clay properties have caused compaction of the overburden even under hydrostatic conditions.

CONCLUSIONS

Hydraulic fracturing of confining layers or aquitards near weakened zones such as caves, karst cavities, open-joints, fissures, ancient collapse funnels, etc, occurs as a result of aquifer head decrease. It is very hazardous and of great importance for the evaluation of overburden stability. The analysis of the process, here called casual hydrofracturing, simply links the relationship for failure between the magnitude of water head decline, the cohesion of relatively impermeable rock, and the thickness of the aquiclude These simple relationships can be used in engineering practice.

Both the theory and experiments testify to the possibility of partial, or even complete, disturbance of thick weakly permeable layers near a single fissure or cavern under a reasonable drop in water level. Commonly the aquifers composed of carbonate rock are strongly fissured and karstified. Developing in vicinity of weakened zones the hydraulic fracturing can weaken interbeds inside clay strata and produce dilated zones in unbound overburden. This can be the cause of extremely high rock compressibility and associated subsidence.

Considering the geological and hydrogeological conditions that occur in the north-west region of Moscow city, it has been found that the long-term pumping of the fissure water is detrimental. Hydraulic fracturing of the aquitards results in either cover-collapse sinkhole development or land subsidence. Carried out before changing the hydrological environment, such an analysis is useful for groundwater monitoring and the forecasting of hazardous geological processes in urban areas.

Acknowledgements: This research is supported by Russian Foundatoin for Fundamental Researches, Project No 05-05-6435a.

Corresponding author: Dr Alexander V. Anikeev, Institute of Environmental Geoscience RAS, Ulansky pereulok 13, building 2, P. O. Box 145, Moscow, 101000, Russian Federation. Tel: +7 095 208 96 05. Email: anikeev_alex@mail.ru.

REFERENCES

ANIKEEV, A.V. 1991. Clay collapse over caves and caverns. In: Geological Hazards. Procttdings of Beijing International Symposium, Beijing, China, October 1991, 336-342.

ANIKEEV, A.V., 1993, Two forms of destruction of bound soils over cavity. Geoekologiya, **2**, 115-123 (in Russian).

ANIKEEV, A.V. 1999. Casual hydrofracturing theory and its application for sinkhole development prediction in the area of Novovoronezh Nuclear Power House-2 (NV NPH-2), Russia. In: Procedings of the 7th Multidisciplinary Conference on Sinkholes and Karst , April 1999, Harrisburg-Hershey, Pennsylvania. A.A.Balkema, Rotterdam, 77-83.

ANIKEEV, A.V. & FOMENKO, I.K. 1995, Subsidence-sinkhole development in sand deposits above karst masses. In: Proceedings of the 5th International Symposium on Land Subsidence, October 1995, the Hague, IAHS Publ. No. 234. A.A.Balkema, Rotterdam, 27-34.

ANIKEEV, A. V., & KOLOMENSKY, E. N. 2002. Some regularities of unbound soil flow into subsurface voids. Bulletin of the Moscow State University, Series 5, Geology, **4**, 51-61 (in Russian).

ASCE 2003. Sinkholes and the Engineering and Environmental Impacts of Karst. Proceedings of the 9th Multidisciplinary Conference, 6 – 10 September 2003, Huntsville, Alabama. American Society of Civil Engineers. Geotechnical Special Publication No. 122.

PSU 2004. Karstology – XXI Century: Theoretical and Practical Significance. Proceeding of the 5th International Symposium, 26-30 May 2004, Perm, Russia. Perm State University, Perm.

OSIPOV, V. I. & MEDVEDEV, O. P. (EDS.-IN-CHIEF) 1997. Moscow: Geology and City. Moskovskiye uchebniki i kartografiya, Moscow (in Russian).

SHENG, Z. & HELM, D. C. 1995. Conceptual models for earth fissuring in Las Vegas Valley, Nevada, ASA. In: Proceedings of the 5th International Symposium on Land Subsidence, October 1995, the Hague, IAHS Publ. No. 234. A.A.Balkema, Rotterdam, 27-34.

THARP, T. M. 1999. Mechanics of upward propagation of cover-collapse sinkholes. Engineerin Geology, **52**, 23-33.

THARP, T. M. 2002. Poroelastic analysis of cover-collapse sinkhole formation piezometric surface drawdown. Environmental Geology, **42**, 447-456.

THARP, T. M. 2003. Cover-collapse sinkhole formation and soil plasticity. In: Sinkholes and the Engineering and Environmental Impacts of Karst. Proceedings of the 9th Multidisciplinary Conference, 6 – 10 September 2003, Huntsville, Alabama. American Society of Civil Engineers. Geotechnical Special Publication No. 122.