ON THE MECHANISMS AND KINEMATICS OF DRIFT DOLINES FORMATION

MEHANIZMI IN KINEMATIKA NASTAJANJA VRTAČ V MORENSKEM GRADIVU

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Izvleček UDK 551.442(438)

Jerzy Liszkowski: Mehanizmi in kinematika nastajanja vrtač v morenskem gradivu

Pri nastajanju vrtač v morenskem gradivu sodelujejo različni mehanizmi, ne samo sufozija. Glavni dejavniki so: litologija ter fizikalne in geomehanske lastnosti prekrivnih sedimentov, geohidrološke razmere ter način močenja stika med kamnino in nanosom ter stopnja zakraselosti matične kamnine. V zvezi z nastajanjem vrtač sta le dva načina sprememb na površju: počasno, a stalno posedanje in hitri, posamični udori.

Ključne besede: geomorfologija, kraška morfologija, pokriti kras, vrtača, sufozijska vrtača, Poljska

Abstract UDC 551.442(438)

Jerzy Liszkowski: On the mechanism and kinematics of drift dolines formation

Different mechanisms and processes, not only suffosion, operate in the development of drift dolines. The main factors which control both the mechanisms and kinematics of drift dolines formation are: the lithology, and the physical and geomechanical properties of the cover deposits; the geohydrologic conditions and the nature of wetting at the bedrock/cover deposits interface; and the degree of karstification of the limestone bedrock. But there are only two modes of ground surface displacements related to them: slow, continous subsidence and rapid, discontinous collapse dolines.

Key words: geomorphology, karst morphology, covered karst, doline, drift doline, Poland

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INTRODUCTION

Closed topographic depresions called dolines or sinkholes are the most common and characteristic landform of karst terranes. Dolines differ in shape, dimensions, spatial distribution, tectonic setting and age and may be formed by diverse physical processes. In most recent text-books, monographs and papers on karst, three or four main types of dolines are distinguished: 1) solution dolines, 2) collapse dolines, 3) subsidence dolines and 4) suffosion dolines (Jennings 1971, Sweeting 1973, Ford & Williams 1989), although it is evident that these are the end member types only (Ford & Williams 1989, 399). Solution and collapse dolines are end member topographic depressions of bare karst terranes: the processes and/or mechanisms involved in their formation are clearly defined (Cramer 1941) and generally accepted. The types 2), 3) and 4) cited are listed as characteristic for covered (mantled) karst terranes. But from a review of many papers it is evident that a true understanding of the mechanisms and/or processes involved in doline formation and development of covered karst terranes has not been achieved. This is reflected in the rather free, discretionary and often wrong usage of such terms as suffosion, (internal) erosion, piping, subsidence, settlement, sagging, etc. Note also that in case, i.e. of covered karst, the terms collapse- and subsidence doline refer to the nature of ground surface displacement and not to the mechanisms of mass loss at the bedrock/cover deposits interface and thus are nongenetic terms.

Dolines are potential or real hazards owing to possible vertical displacement, either continous (subsidence) or discontinous (collapse, fracturing) of the ground-surface. Since risk or hazard evaluation related to ground-surface displacement be achieved only if the mechanisms and kinematics of the processes involved are exactly specified, identification and classification of different types of dolines will be a very important geologic and engineering-geological research problem.

The paper presents a contribution to this problem from the engineering-geological point of view. The main objectives of this contribution are as follows: a) to define the different processes and mechanisms of doline formation, b) to determine the controls of doline formation and define the basic geologic, geohydrologic and geomechanic models of their development and c) to determine and quantify to some degree the magnitude (amount) and kinematics (rate) of ground surface displacement related to them.

The considerations below will be limited to dolines of covered karst terranes: the broad, nongenetic term "drift dolines" will be used for these. Moreover the considerations will be limited to carbonate karst terranes although they are true for gypsum and/or anhydrite karst terranes too. As most of the results and considerations presented are based on the author's experiences and engineering-geological studies in several karst areas from Poland, only a very limited number of references will be cited in the text.

MECHANISMS OF DRIFT DOLINE FORMATION

Drift dolines are a particular group of natural and/or induced localized vertical mass movements restricted to covered karst terranes. The superficial expression of downward directed vertical mass movements are called subsidence in geomechanics, unaffected by their origin, radius, amount and rate.

It is convenient in engineering-geological practice to recognize different *types of subsidence on the basis of the primary cause of disequilibrium*. The primary cause of subsidences sensu lato is in every case the mass deficit or loss at a given depth below the groundsurface. For dolines the primary cause of subsidence is per definito the solutional mass loss within the bedrock, expressed as solutionally widened joints and fissures, solutional cavities, passages, etc., which act as main strain nuclei. However, in the case of drift dolines the strain nuclei are separated from the centres of solutional mass loss and shifted to the base of the overlying cover deposits. The strain nuclei are now - with only one exception - located along the bedrock/cover deposits interface.

All processes of mass loss operating at this interface are triggered by hydrodynamic forces and belong to the group of seepage (hydrodynamic) deformations of soils (Liszkowski 1973, 1979).

No universally accepted classification of this group of processes exist. However, a more frequently used classification (Ziems 1967, Liszkowski 1973, Busch & Luckner 1974, Witt 1986) divides this group of seepage deformations of soils into two categories according to the general direction of the force potential (hydraulic head) or of the seepage force. If these forces are directed downward they may initiate either suffosion, internal erosion or fluidization. If directed upwards, they may initiate eiher hydraulic penetration or breakthrough, hydraulic-heave or liquefaction.

Suffosion is defined as the selective transport and removal of fines from poorly sorted, noncohesive unconsolidated granular deposits by downward percolating infiltration or downward seeping groundwater. The process develops as a grain-by-grain transport phenomenon. Suffosion changes the texture and permeability of soils but does not lead indispensably to structural failures. But if the process develops progressively, more and more grains of successively greater diameters are entrained in the process and suffosion changes into **progressive suffosion** which affects the structure of the soil and results in its failure.

Internal erosion is the general (involving rather the whole of the soil than individual grains) transport and removal of soil particles by downward moving groundwater. The process leads immediately to volumetric deformations of a part of the soil mass. If the soil involved by the process possess some cohesion, like clayey or loamy sands, tunnel-like channels are formed within the soil mass. For this subtype of internal erosion a very appropriate geomorphic term is **tunnelling**. If the soil is a true noncohesive one, like clean, well sorted sands, a cylindrical body of loose soil particles suspended in the groundwater stream will occur (this is a form of localized fluidization). Internal erosion develops almost exclusively backwards (retrogressive), i.e. from the source of particle removal (strain nucleus) towards the soil mass interior.

Fluidization is the process of volumetric changes from the solid to fluid (suspended) state of noncohesive soils in a rapidly downward flowing groundwater stream. The fluidized granular material flows as a whole. This type of seepage deformation of soils is a very scarce one since fluidization needs very high groundwater flow velocities.

Hydraulic penetration or **break-through** is the process of localized liquefaction of granular (soil) material acompanied or succeeded by the transportation and removal of particles in an upward directed groundwater stream. The process results in the formation of upwards migrating cylindrical zones of suspended soil particles (within noncohesive soils) or pipes (within cohesive soils); that is why the process is commonly called **piping**.

Note that between tunnelling and piping noticeable geometric similarities exist: within cohesive soils both process result in the formation of tube-like subterranean voids. But they differ in sense of the causal seepage forces and this justifies the use of different terms for them. In most geomorphic and geologic publications and monographs both processes are incorrectly called piping. A noteworthy peculiarity of piping in mantled karst terranes is that the sense of particles transport is against the upwards directed seepage forces.

Hydraulic heavy is the process of a really large scale heave of a cohesive, impermeable soil layer as a whole by the buoyant effect of upward directed seepage pressures. As this means that the hydraulic head should exceed the overburden pressure of the overlying soli column, the process occur rather infrequently under natural conditions. However, hydraulic head fluctuations resulting in repeted increase and decrease of bouyant support lead to repeated wetting and drying and hence to repeated swelling and shrinkage. This leads then to cracking, strenght softening etc. which favor disintegration, breaking, shattering and settling out of soil pieces and aggregates.

Liquefaction is defined as the sudden large decrease of shearing resistance of water-saturated fine-grained, silty, cohesionless soils, caused by seismic shocks or strains, and asociated with a sudden but temporary increase of the pore water pressure which transforms the soil into a fluid mass. However, the primary cause of increase of the pore water presure may be a drastic increase or decrease of the hydraulic head unrelated to any seismic event, too.

None of the listed types of seepage or hydrodynamic deformations of soils are restricted to karst terranes. On the contrary, they are common in many other geoenvironments. However, the commonly high secondary solution porosity of limestone bedrock forms extermely favorable conditions for removal and delivery of particles eroded from the overlying cover deposits.

As mentioned above, the strain nuclei of most drift dolines are located along the bedrock/cover deposits interface. At this interface an abrupt, stepwise change of lithologies and pore structures occur: from lithifield, jointed and karstified rock masses below to loose, unconsolidated, porous surficial deposits above the interface. It is this interface which controls and favors the development of seepage deformations of soils. For this particular variety of seepage deformation of soils the adjective "**contact**" meaning: "caused or activated by contact" is used in soil mechanics and engineering geology. Hence, the seepage deformations of soils cited and briefly defined could be in this case exactly named: contact suffosion, progressive contact suffosion, (subterranean) contact erosion, contact hydraulic penetration or break-through. For the process of fluidization, hydraulic heave and liquefaction, as well as for tunnelling and piping, the usage of the adjective "contact" seems to be meaningless.

The last-listed processes define the true origin of drift dolines but not necessarily the modes of ground surface displacements which are only the final expressions of the processes operating within the soil column. For complex, e.g. stratified and inhomogenous drift sequences of great thickness (>25 m), the near-surface mechanisms of deformation, which directly define the modes of ground surface displacements, may be almost completely decoupled from the initial processes of seepage deformations of soils which developed at the interface.

THE GEOENVIRONMENTAL MODEL (SYSTEM) OF DRIFT DOLINES FORMATION

To recognize and/or slarify the mechanisms of drift dolines formation it is necessary to identify the main controlling factors of their development from the intial to final phases in a manner which offers their forecast or prediction and/or calculation. In our case there are three main controls (Liszkowski 1979):

1) the lithology, thickness and physical properties of the cover deposits;
2) the (geo-)hydrologic conditions at the bedrock/cover deposits interface;

3) the structure and degree of karstification just below the bedrock/cover interface.

The first factor controls partly the category of seepage deformations of soils which may develop at the bedrock/cover deposits interface, i.e., the initial processes (mechanisms) of deformation, the likely superposition of different types of deformations and the nature and partly geometric and kinematic characteristics of subsidence of the ground surface. Lithologies of cover deposits may be divided into two broad end-member categories: I - unconsolidated, noncohesive, permeable soils, II - unconsolidated, cohesive, impermeable soils. The first category of cover deposits include gravels, sands and silty sands, the second - clays and loams. Noncohesive soils deform by grain-to-grain displacements, their strenght is the function of normal stresses and the friction angle only and - over their high hydraulic conductivity - pore water pressures within them are quickly dissipated. In contrast, cohesive soils deform as a whole; their shearing strenght is the function of cohesion and friction resistance, effective normal stresses and the complete stress history and - over their tightness - high pore water pressure may be built-up and stored within them.

The second factor circumscribes the nature and location of the potentiometric surface of ground-waters relative to the bedrock/cover deposits interface and therefore the wetting conditions at this interface. These control the continuity of mass loss processes initiated at this interface, the values and sense of the seepage force vector and thus the category and rates of seepage deformations of soils which probably will start at the bedrock/cover deposits interface. For the category of noncohesive cover deposits we may assume that the groundwater will form a free water table. Then three cases may occur: IA - the water table is located much below the top of bedrock, i.e., the bedrock/cover deposits interface is only exceptionally wetted; IB - the water table lies at the top of bedrock, i.e., the interface is intermittently wetted; IC - the water table lies much above the top of bedrock within the noncohesive cover soils, i.e., the interface is permanently wetted. For the category of cohesive cover deposits three cases of (geo-)hydrologic conditions may occur, too: IIA - the groundwater is unconfined; the water table lies much below the top of bedrock (bedrock/cover deposits interface only exceptionally wetted); IIB - the groundwater is confined; the pressiometric surface lies at the top of bedrock (interface intermitteny wetted); IIC - the groundwater is confined; the pressiometric surface lies significantly above the top of bedrock, within the cohesive cover deposits (interface permanently wetted).

The third factor circumscribes the degree of jointing and karstification of the limestones bedrock. Two cases are of special interest: 1 - the bedrock is jointed but there are no open solutional voids in contact with the overlying cover deposits; 2 - the bedrock is jointed and karstified and there are some open solutional voids in contact with the overlying cover deposits. It should

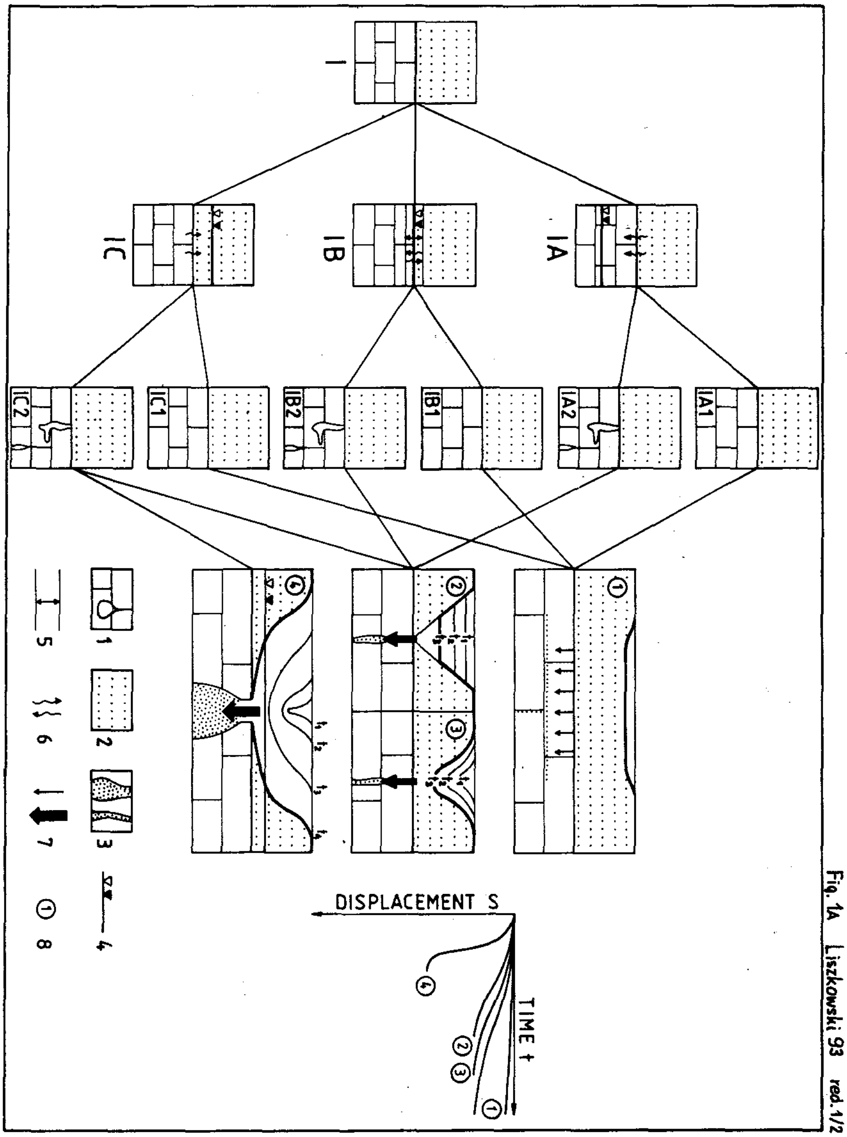
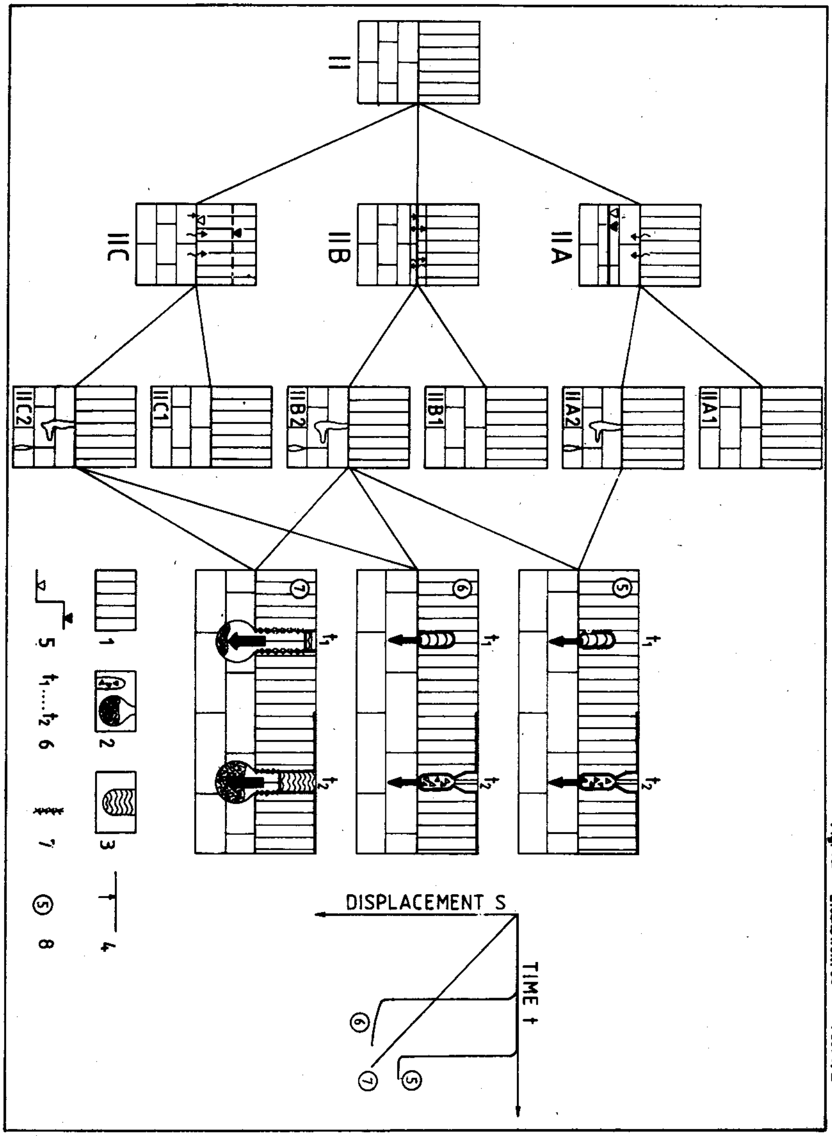


Fig. 1. Models of drift doline formations in mantled karst terranes A/Case I: Noncohesive, permeable cover deposits.

1 - limestone bedrock, with or without solution voids, 2 - noncohesive soils (e.g. sands), 3 - filled solution voids, 4 - ground water table, 5 - range of ground water table fluctuations, 6 - general direction of seepage forces, 7 - mass loss resulting from seepage deformations of cover deposits; thickness of mark indicate mass flux intensity, 8 - types of seepage deformations of soils: 1 - contact suffosion, 2 - progresive contact suffosion, 3 - internal (subterranean) contact erosion, 4 - fluidization.



B/Case II: Cohesive, impermeable (and semipermeable) cover deposits.

1 - cohesive soils (e.g. loams), 2 - voids filled with collapsed (a) and suspended (b) particles, 3 - drift dolines filled immediatly after their ocurrence with limnic and organic sediments, 4 - pressurized ground water table, 5 - pressiometric head, 6 - phases of drift dolines formation from intial (t_1) to final (t_2) ones, 7 - planes of shearfailure, 8 - types of seepage deformations of soils: 5 - tunneling, 6 - piping, 7 - hydraulic haeave. Other symbols are explained in the text.

not be stressed that the degree of karstification controls the likely rate of removal of soil particles from the overlying cover deposits across the interface and the likely volume of deposits which may be stored within solution voids of the bedrock. The degree of karstification controls also partly the geometry of ground-surface dislocation, especially in the case of thin (<5m), homogenous, noncohesive cover deposits (Liszkowski 1975).

It seems to be questionable to limit the controlling factors of drift dolines formation and development to three only. But note that these three factors are complex ones, including many individual quantities. For example, one may wonder why the climatic factor, whose influence on the intensity of collapse incidents is well documented, is excluded from the model. However climatic events, such as heavy rainfalls, hurricanes, etc., are immediately expressed in

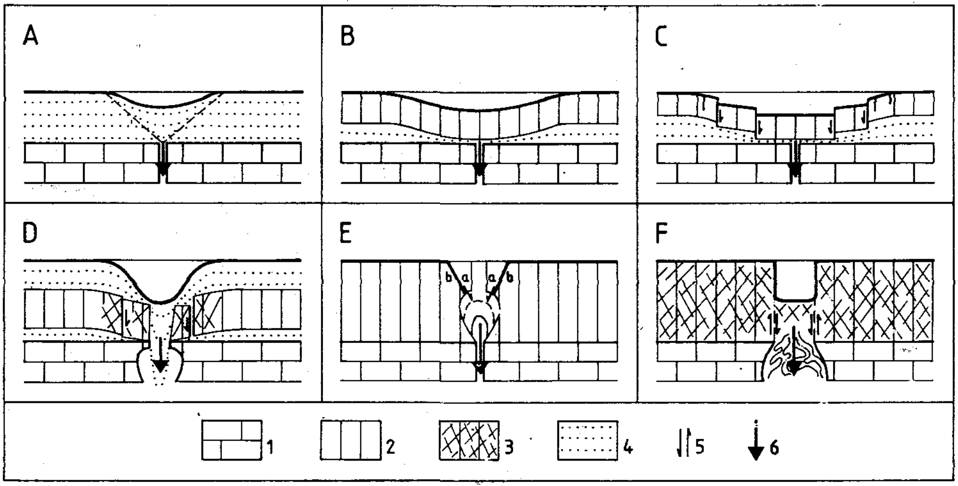


Fig. 2. Mechanisms of ground surface displacments related to drift dolines.
A - sagging or compaction. B - bending of deformable elastic layer, C - bending with tension or shear failure, D - as in C followed by granular (dry or wet) flow, E - tension or shearing failure to subsidence dolines of authors. C to F equals to collapse dolines or sinkholes of authors.
Explanation of signs: 1 - karstified limestone bedrock, 2 - normaly consolidated cohesive soils, 3 - overconsolidated and fissured cohesive soils, 4 - noncohesive soils, 5 - sense of shear, 6 - mass loss by seepage deformations of soils at the bedrock/cover deposits interface.

seasonal or short-term changes of (geo-)hydrologic conditions of the karst geosystem, i.e., in hydraulic head and gradient fluctuations, pore pressure changes, etc., all of which are included in the second factor. Also topography of the bedrock/cover deposits interface may be important in respect to the problem discussed; but the thorough analysis of this factor leads to the conclusion that it influences the probability of arching within the cover deposits and thus the time interval between the initial void formation and the final ground surface subsidence incident only, not the root process itself.

Thus, coupled together, the three factors describe rather completely but in comprehensive manner the geoenvironmental controls of drift dolines formation for the two end-member lithologies of cover deposits in mantled carbonate karst terranes and the processes of energy and mass transfer within them.

Hence, the three factors (=subenvironments) coupled together form the end act as a model for drift dolines formation searched for. This model is - for the two end-member lithologies cited - presented in Fig. 1.

DISCUSSION AND FINAL REMARKS

The model presented may be used in two different ways:

i) If little and only generalized or preliminary data concerning the three main elements (factors) of the mantled karst geoenviroinment are known, the model may help to select the main problems and establish the framework for advanced studies.

ii) If there are sufficient quantitative details known, concerning the three main elements cited, the model may be used for prediction of the likely mechanisms of seepage deformations of soils which will develop at the bedrock/cover soils interface and their likely further development within the soil column and the likely mechanism of ground surface displacement (subsidence s.l.).

However, prediction involves not only types, but place, time, intensity and range of ground surface dislocations too. Our ability to predict place and time of localized subsidence s.l., especially of collapse incidences in covered karst terranes is very minute. This gap in our ability to predict karst subsidences s.l. can be narrowed by accumulating a great amount of information on man-induced drift dolines formation (Yuan 1987, Chen & Xiang 1991, Newton 1984). Somewhat higher is our ability to predict the intensity and range of karst subsidences s.l. But in fact, the first step in any prediction should be the prediction of mechanisms involved in the formation of drift dolines and of modes of ground surfaces deformation. And this ability is offered by the model presented.

Inspection of Fig. 1A & B indicates that there are three main types of seepage deformation of soils involved in drift doline formation: progressive contact suffosion, (subterranean) contact erosion and contact hydraulic penetration, preceeded or accompanied by two other ones: fluidization and liquefaction. In more complex real geological settings, i.e. layered sequences of noncohesive and cohesive cover deposits, superposition of these processes in the vertical profile will occur, depending on site lithologies and geohydrologic conditions. But, unaffacted by the types of seepage deformation of soils involved, only two modes of ground surfaces deformations occur: continous and relatively slow subsidences s.s. and discontinous rapid ground surface failures, i.e. collapses. Thus it will rarely be possible to determine the root cause of drift doline formation from the modes of ground surfaces deformations alone. This reinforces the conclusion of Cramer (1941) (see also Ford & Williams 1989) that the types of ground surface deformation observed do not refer to the true origin of drift dolines. Nevertheless it is possible to clarify and/or detail the mechanisms of soil failures involved in the processes of ground surface deformation, which are much more closely connected with the mechanisms of mass loss at the bedrock/cover deposits interface (Tolmatchev & Reuter 1990). Some of these mechanisms recognized in authors regional and site investigations are presented in Fig. 2.

Thus also now much is known about the real initial mechanisms or processes of drift dolines formations and the real final mechanisms and modes of their occurrence on the ground surface, much more data should be collected and treated before a true genetic classification of these natural phenomena will be achieved.

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MEHANIZMI IN KINEMATIKA NASTAJANJA VRTAČ V MORENSKEM GRADIVU

Povzetek

V krasoslovni literaturi so običajno trije tipi vrtač: korozijske, udorne in sufozijske. Mehanizmi nastajanja prvih dveh tipov so dobro znani, medtem ko je za tretjega to poznavanje veliko slabše. Pri nastajanju vrtač v morenskem gradivu sodelujejo različni mehanizmi, ne samo sufozija, kot še vedno običajno navajamo. Glavni dejavniki so: litologija ter fizikalne in geomehanske lastnosti prekrivnih sedimentov, geohidrološke razmere ter način močenja stika med kamnino in nanosom ter stopnja zakraselosti matične kamnine. Vsi trije dejavniki skupaj sestavljajo model (sistem), ki opisuje procese prenosa energije in mase v pokritem krasu in omogoča predvidevanje mehanizmov, ki povzročajo spremembe na površju zaradi spiranja na stiku matične kamnine in nanosa. V zvezi z nastajanjem vrtač sta le dva načina sprememb na površju: počasno, a stalno posedanje in hitri, posamični udori.

Prispevek definira posamezne procese in mehanizme deformacij površja zaradi spiranja prsti, kar je osnovni proces nastajanja takih sufozijskih vrtač, kot tudi mehanizme posedanja oziroma udiranja površja, kar je končni in na zunaj vidni odraz sufozijskih vrtač.