Karst failures: Model testing and conceptual models

Ruptures dans les karsts: Essai sur modèle et modèles de conception

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SYNOPSIS: Extensive exploration of karstic terraines necessitates a detail knowledge of mechanisms of dangerous karst failures, primary the sinkhole formation. Such knowledge is materialized in conceptual models of karst processes. In view of the fact that karst failures usually are out of direct observation the model testing serves as principal source of information about their running. The paper presented deals with the principles and methods of model testing of karst failures, as well as with summarization of a single conceptual model.

1. DISCUSSION

The problems arizing during exploration of karstic terraines cannot be correctly solved without precise ideas upon the mechanisms of formation of dangerous karst manifestations as caves, voids, destabilized zones, sinkholes, subsidences, etc. These ideas are usually expressed by so-called conceptual models which may be of rather various forms: from diffuse verbal descriptions and upto drawn schemes. Conceptual models for karst processes are usually arranged on information by in-situ observations of separate karst failures or on the basis of model-testing data.

The mechanisms of karst failures are as a rule latent and not accessible to direct observation as well as failures themselves occur within the rock mass frequently at large depth. Therefore the opportunities for construction of karst conceptual models only on the basis of in-situ observations are rather limited. The only exceptions may be observations held within caves or at land surface where in fact the karst manifestations dangerous for buildings and structures are being formed. In doing so an observer obtaines information about the processes which run only at the initial and final stages of a single complex of karst failures, as for example the formation of a sinkhole. Conceptual model suggested only on the basis of these data will of course prove not to be complete.

Model testing wins a growing importance in engineering karstology. This method of scientific knowledge serves as essential instrument for studying mechanisms of karst failures, it is used successfully for prediction of karst danger as well (Khomenko 1986). As compared with other prediction methods used in engineering geodynamics the most advantageous features of model testing are in its demonstrativeness and opportunity to estimate not only the existing state of karst conditions but and in unexpected ones which in particular may be formed under man's activities.

2. THEORETICAL AND PRACTICAL ASPECTS OF MODEL TESTING APPLICATION IN ENGINEERING KARSTOLOGY

In the USSR a practice book having some instructions for application of model testing for quantitative estimation of karst danger in civil engineering was worked out for the first time as far back as 1984 (Rekomendacii... 1984). It was stated there that the model testing is advisable to be used as a method of prediction of karst processes in three cases which are as follows: (1) when designing special structures or buildings provided, it is used in combination with design and statistical methods of prediction; (2) in complex geo-engineering conditions when the application of design method is difficult (complicated structure of the soil massive, poor study of the mechanism of karst process, etc.); (3) in conditions when the application of statistic methods is difficult (lack of representative statistics, necessity for evaluation of an expected karst danger, etc.).

It is known that the maximum conformity of geological process model testing with its natural prototype is achieved by in-situ experiments. However, because of complicacy and insufficient working out of the technique for experimental reproduction of karst processes in-situ, a laboratory experiment is more accessible at present. In view of insufficient study of the mechanisms of karst failures their laboratory modeling is better to be carried out on two-dimensional models. Such test installations provided with a transparent front wall allows for direct observation of a general pattern of a simulated process running and its photographic fixing. The three-dimensional models and the appropriated installations possess a number of advantages over two-dimensional ones ensuring more perfect correspondence to natural conditions. Nevertheless, the laboratory practice of two-dimensional modeling realized with a thorough regard for specific errors that may occur during an experiment is concerved.

According to their mechanism and running conditions the karst failures may be subdivided into three groups, namely: (1) dissolution of the soluble rock; (2) gravity failure of the soluble bedrock and overlying soils (karst collapse); (3) hydraulic failure of the overlying soils and withdrawal of the fill or residue out of caves, voids and fractures in the soluble rock (karst piping).

In laboratory conditions the dissolution of soluble rocks is reproduced by means of chemokinetic modeling. The karst collapses may be reproduced on centrifugal models and on models composed of equivalent materials. The centrifugal modeling was never used in engineering karstology yet, though its application in this field seems to be prospective. Karst piping is reproduced adequately only on hydraulic installations.

3. MODELING OF SOLUBLE ROCK DISSOLUTION

Through the use of laboratory chemo-kinetic modeling of the soluble rock dissolution it is accomplished: (1) determination of soluble rock dissolution rate both in natural conditions and under man's activities; (2) estimation of antikarst protection measures aimed at changing the hydrochemical composition of karst water and conditions of its circulation; (3) determination of the length of a groundwater saturation path; (4) evaluation of the fracture and void enlargement rate.

All these are related to the diffusely dissoluble (non-carbonate) rocks since the technique of laboratory model testing of the dissolution of non-diffusely dissoluble rocks is worked out imperfectly. This problem is not so pressing as compared to the problem of modelling of the non-carbonate rock dissolution because the dissolution of carbonate rocks in natural conditions proceeds very slow and commonly is not capable of causing unfavourable after-effects during the service life of buildings and structures.

The basic principles of chemo-kinetic modeling are perfectly worked out in the physical chemistry. According to these principles the dynamics of salt dissolution process when the solvent flows through a slot is governed by the condition:

$$r_x = 2K(C_s - C_x)/\rho \qquad (1)$$

where r_x - rate of slot enlargement in its cross-section located at distance x from the inlet; K - coefficient of dissolution rate; ρ - density of dissoluble substance; C_s - concentration of saturation (dissolubility); C_x - concentration of dissoluble substance in a solvent in a cross-section under consideration.

The main point of modeling of non-carbonate rock dissolution when the groundwater flows through fractures and voids lies in the experimental determination of a quantity K on the observance of some similarity parameters, namely:

Margules number:

$$Ma = K_n d_n / q_n = K_m d_m / q_m \qquad (2)$$

where d - slot width; q - solvent flow rate per unit length of slot cross-section (post-subs n and m relate to parameters of natural and model subjects of inquiry respectively).

Fourier number:

$$Fo = D_n t_n / d_n^2 = D_m t_m / d_m^2 \qquad (3)$$

where D - diffusion coefficient of dissoluble substance; t - time.

Strouhal number:

$$Sh = t_n q_n / d_n^2 = t_m q_m / d_m^2 \qquad (4)$$

Reynolds number:

$$Re = q_n / \nu_n = q_m / \nu_m \qquad (5)$$

where ν - kinematic viscosity of solvent.

In course of modeling the relationships between similarity parameters are determined by formula:

$$Ma = A(Fo)^e (Sh)^f (Re)^g \qquad (6)$$

where A,e,f,g - experimentally determined non-dimensional coefficients.

In case, when samples of natural soluble rocks are used as soluble substance and water having a temperature and chemical composition to be close to those of the natural karst waters, serves as solvent, formula (6) will take the following form:

$$Ma = A(Re)^g \qquad (7)$$

During model testing the coefficient of dissolution rate is determined by:

$$k_m = \Delta d / (C_s - C_x)\Delta t \qquad (8)$$

where Δd - change in the slot width; Δt - test duration.

The transfer to natural conditions is carried out through the use of formula:

$$k_n = (Ma) q_n / d_n \qquad (9)$$

In so doing a quantity of Margules number is determined while testing.

The experimental installation intended for simulation of soluble rock dissolution is shown at Figure 1, where (1) shiftable reservoir with solvent; (2) sample cylindric box; (3) solution receiver.

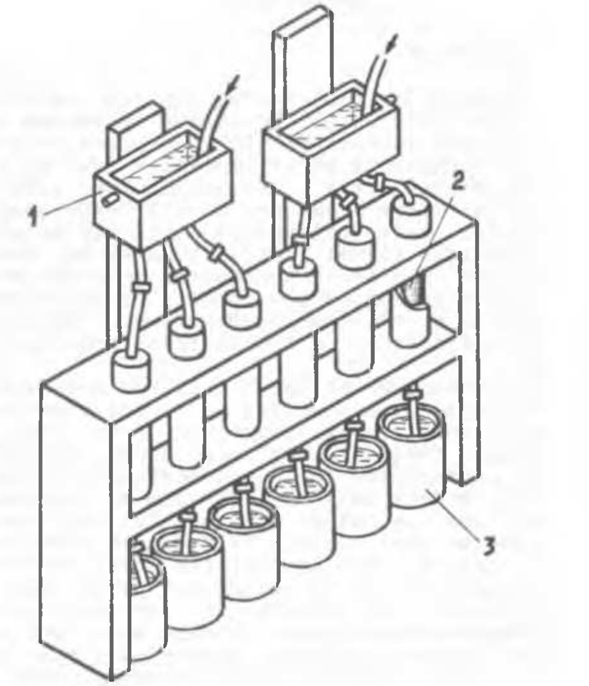


Figure 1. Installation intended for modeling of the soluble rock dissolution (front view with a partial cut-out in a sample box).

Using this installation a process of dissolution of the walls of vertical fractures or voids is simulated with downward groundwater flow. Installations of this type may incorporate more then six sample boxes and more than two reservoirs with solvent.

Prior to testing a sample of natural soluble rock or specially selected soluble substance consisting out of two parts being separated at their edges by two strip plates is placed into every sample box. The sample prepared in this way has an internal slot of rectangular cross-section passing along all its length. A space between the sample lateral surfaces and the sample box walls is filled with melted paraffin.

When the installation incorporating six sample boxes and two reservoirs with solvent is used for the test then three pairs of samples of different lengths are prepared, in every pair the samples being approximately equal in length. The first three boxes with samples of different lengths, being installed into them, are connected to one of the reservoirs while the second three - to another one positioned at different level.

While the solvent is running with a constant flow rate from the reservoirs through the sample boxes into the receivers it should have a value of Reynolds number not exceeding 1300. During the test a concentration of dissoluble substance in the solvent entered into receivers is established through the use of electric salt concentration gauges. After the accomplishment of the test the sample boxes are withdrawn out of the installation and heated till paraffin is melted. Samples are extracted and the slot width are measured. Since the solvent was fed into the slots with different flow rates at the end of testing a set of numerical data characterizing a dynamics of substance dissolution at different flow rate is obtained.

4. MODELING OF KARST COLLAPSE

Modeling of karst collapse carried out with the use of the method of equivalent materials makes it possible to solve a number of practical problems arizing in the course of engineering development of karstifyed terranes. Among them are: (1) evaluation of the danger of karst voids and caves detected during the site investigation both in natural conditions and under man-made impact including direct location of karst voids under buildings and structures; (2) estimation of antikarst measures aimed at increasing soil and rock strength and elimination of voids; (3) prediction of sizes of collapses (including sinkholes).

The method of equivalent materials with which the modeling of karst collapses is carried out is widely used in mining engineering. It is based on utilization of some substances as model materials. Physical and mechanical properties of such substances should be in definite relationship with the properties of natural soils and rocks being simulated.

For hard rock this relationship (similarity parameter) takes the form:

$$R_n/\gamma_n L_n = R_m/\gamma_m L_m \qquad (10)$$

where R - unconfined tensile or compression strength; γ - unit weight; L - linear dimension.

For cohesive soils there are used similarity parameters which are expressed by:

$$c_n/\gamma_n L_n = c_m/\gamma_m L_m \qquad (11)$$

$$\tan\varphi_n = \tan\varphi_m \qquad (12)$$

where c - cohesion; φ - angle of internal friction.

For non-cohesive soils only the second similarity parameter (12) is valid.

When the model reproduces a multilayered stratum then for all of the layers there should be observed following conditions:

$$\gamma_n/\gamma_m = const \qquad (13)$$

In modeling the time factor is usually denied, nevertheless for approximate computations following relation is sometimes used:

$$t_n = t_m (L_n/L_m)^{(1/2)} \qquad (14)$$

In the USSR for laboratory modeling of karst collapse on equivalent materials different researchers utilizaed experimental installations of different type but nevertheless all of them have some common features. An universal two-dimensional installation that assembles all the necessary requirements is shown at Figure 2, where (1) transparent front wall; (2) device for transmitting applied load; (3) sample box with modeling material; (4) elements of rear wall; (5) device for model deformation control; (6) device (support) for simulation of karst void.

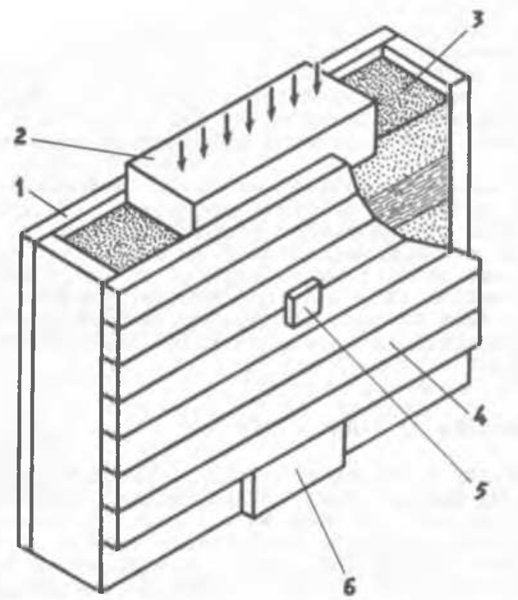


Figure 2. Installation intended for modeling of karst collapse (back view with a partial cut-out in the rear wall).

It should be noted that the design of a device for simulation of a karstic void may vary within a very wide range. In some cases the void is hand-cut out of the equivalent material mass. Most commonly the void horizontal growth is simulated by successive removal (starting from the center) of the support with a layer of equivalent material placed on.

According to the information presented in the basic work by B.Stimpson (Stimpson 1970) a large experience of using different substances as equivalent material had been accumulated in the world. For the purpose of modeling the karst collapse mainly are used non-cemented and cemented granular materials. Sand, talc, mica, dry powder-like clay, sawdust, small balls, etc. (as granular components), and gypsum, quicklime, substances like paraffin, various glues, oils, water, etc. (as binding materials).

Equivalent materials are so selected that their properties are capable to response for wanted similarity parameters (formulae (10-13)) with regard to the modeling scale line chosen. Selection of equivalent material properties can be carried out only then when it is composed of several components. A three-component composition should be considered as optimal.

The procedure of the experiment itself and especially the procedure of its preparation depends not only on experimental installation design but also on the type of compound being used as model material. The model can be composed of: (1) material like concrete; (2) materials cemented by binders which solidify on cooling; (3) materials cemented by binders which solidify at room temperature (glues); (4) materials cemented by non-solidifying binders; (5) non-cemented or poorly wetted (cemented by water) materials.

As a rule the equivalent materials of former three types are used for simulation of hard rocks and firm cohesive soils, the materials of the fourth type are used for simulation of plastic cohesive soils and the materials of the fifth type sre used for simulation of non-cohesive soils. The equivalent materials of the latter two types can be used repeatedly. During the experiment, as the simulated void is progressively and discretedly enlarged, the gravity failure of the model materials that accompany this enlargement are fixed.

Overall, the application of the method of equivalent materials to model testing of the karst collapses yields rather promissing results. By the use of this method one can accomplish both the local prediction as applied to the concrete construction site and the regional prediction which takes account of spacial-time changes of the principal factors governing sinkhole formation.

5. MODELING OF KARST PIPING

Laboratory modeling of karst piping is carried out with subject for: (1) estimation of the danger of natural and man-made changes in the hydrogeological conditions which are capable of causing karst piping failures; (2) estimation of antikarst measures aimed at changing the seepage-hydrodynamic conditions of growndwater flow; (3) prediction of karst piping forms (including sinkholes). In these cases the question is most often related to estimation of karst danger being man-made in its origin.

The method of hydrogeological model testing intended for laboratory simulation of karst piping has been used in applied hydrogeology long since. It is based on utilization of special hydraulic units (soil containers) filled with water-permeable grained materials. They are used for reproduction of groundwater seepage of a terrane in a reduced scale.

Thereat the seepage hydrodynamic parameters of model and natural subjects of the inquiry should be related to each other by following relationship (similarity parameter):

$$t_n k_n / \mu_n L_n = t_m k_m / \mu_m L_m \qquad (15)$$

where k - coefficient of permeability; μ - coefficient of water loss.

If natural soils are utilized as model material, the water having approximately the same temperature and chemical composition as the water in natural conditions serves as filterable liquid, and the time factor is denied, then the main condition of modeling is left to be a geometrical similarity of the model to natural subject of inquiry.

There are many designs of experimental installations intended for laboratory model testing of karst piping. The installation constructed by V.P.Khomenko is characterized by its versatility. Its general arrangement is shown at Figure 3, where: (1) shiftable outlet; (2) side chamber; (3) perforated wall; (4) transparent front wall; (5) device for modeling water infiltration; (6) shiftable reservoir; (7) modeling material; (8) lower chamber; (9) waterproof element with device for modeling slot-break.

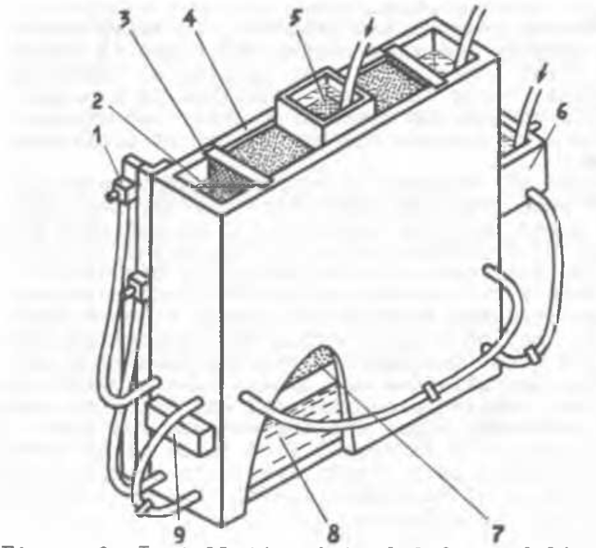


Figure 3. Installation intended for modeling karst piping (back view with partial cut-out in the rear wall).

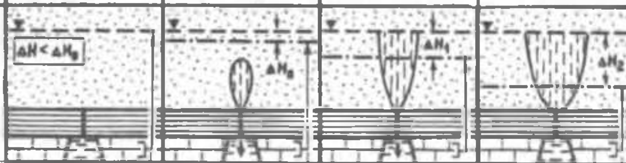
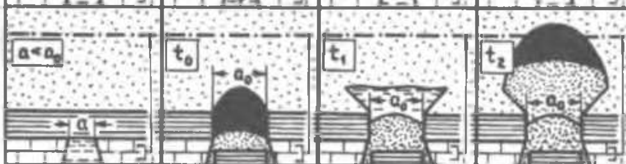
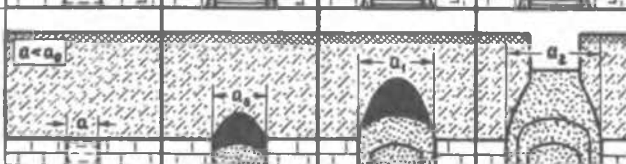
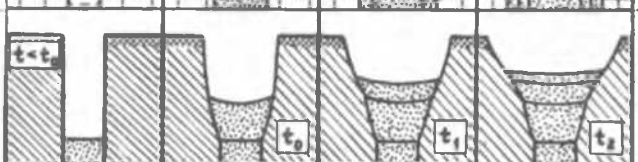
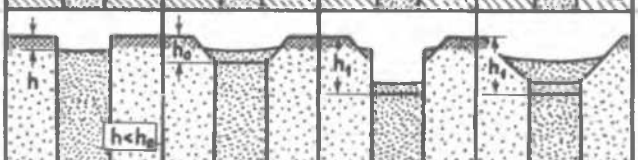
Here the lower chamber simulates a cave in soluble rocks which is filled with water having a certain potential and the working and side chambers simulate an overkarst aquifer within the covering soils. Appearance of a slot-break in the waterproof element when the head of filterable liquid in the side chambers and its potential in the lower chamber have an equal level - may be interpreted in two ways. On one hand this may be considered as if the cavern would come into contact with the covering soils with a single aquifer within the covering soils and the soluble rocks. On the other - this may be considered as the conditions of hydraulic equilibrium of a through break-down in the waterproof layer separating overkarst water from karst water.

Subsequently if it is necessary this equilibrium may be disturbed by changing the position of outlets and reservoir. The four different situations associated with groundwater level fluctuations can be simulated, namely: (1) decline of karst water potential with the overkarst groundwater head constant; (2) growth of the karst water potential with the overkarst groundwater head constant; (3) decline of the overkarst groundwater head with the the karstwater potential constant; (4) growth of the overkarst groundwater head with the karstwater potential constant. With the aid of supplementary devices one may simulate a situation when the water flowing enters the covering soils with or in absence of the aquifer in them.

6. CONCEPTUAL MODELS

Utilization of laboratory model testing made it possible to advance far in understanding the nature and the mechanisms of karst failures. Purposeful experimental studies accomplished in recent years helped to work out an integral conception of a single system of karst failures giving birth to the formation of sinkholes at land surface in regions where the covered karst is being

Table 1. Conceptual models of karst failures in overlaying soils.

Type of karst failures		Stage of the failure development: fore-run / initial / subsequent / final	Failuring factors. Nature of its changes
Piping of non-cohesive soils	by falling groundwater flow		Decline of the karst-water potential and/or growth of the over-karst water level
	by arizing groundwater flow		Growth of the karst-water potential and/or decline of the over-karst water level
Collapse	of sands in arizing groundwater		Time, spontaneous development
	of any type of soils including sands in falling groundwater flow		Growth of the destabilized zones in soils and bedrock
Sinkhole formation	in cohesive soils		Time, spontaneous development
	in non-cohesive soils		Growth of observed subsidence

soluble rock	cohesive soil	percolated soil	land surface
waterproof layer	non-cohesive soil	groundwater level	floaded void
soil	collapsed soil	potential level	cave or void

developed (Tolmachyov et al. 1986). This was achieved by the combined efforts of researchers from All-Union Research Institute of Bases and Underground Structures and the Research Institute for Engineering Site Investigations.

The proposed conceptual models are represented in the form of diagrams featured in the Table 1. The diagrams are based not only on information obtained in laboratory model testing but and on the data of in-situ observations of the development in time of karst caves as well as on results of special engineering speleological investigations. Utilization of these conceptual models in the purposes of civil engineering and in design of foundations for buildings makes it possible to adopt correct decision when selecting and specifying antikarst measures (Sorochan et al. 1982, 1985). It helps to accomplish a scientificaly grounded prediction of development of karst failures on computational theoretical basis.

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