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DEVELOPMENT OF KARSTOLOGICAL GEOTECHNICAL MONITORING SYSTEM USING PHYSICAL MODELING

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Abstract

Well-known approaches to karst monitoring were analyzed, focusing on the assessment of dispersed soil layers overlying soluble rocks in covered karst areas. The advantages of using deep core markers as deformation sensors were examined. It was concluded that laboratory physical modeling in specially designed trays is an effective method for testing such monitoring systems. The experimental setup, including the testing equipment, deep core markers, and model materials, is briefly described, and the rationale for their selection is explained. The main experimental results are presented. In all tests, the monitoring system showed a clear response at the moment when the simulated karst cavity came into contact with the overlying dispersed soils, and characteristic spatial patterns of marker settlement were identified. In two experiments, surface settlement of the model was additionally observed. The results confirm that the proposed benchmark-based karst monitoring system can principally detect stress changes in overlying soils caused by the appearance and increase of a cavity.

Keywords: Karst, Sinkhole, Monitoring, Bench Marks, Physical Modeling, Prediction, Engineering Protection.

I. Introduction

Construction in karst areas, i.e., where soluble rocks are present in the geological section, has its own specific characteristics and is associated with several difficulties [XIX-XXI]. Monitoring karst processes, also known as karstological monitoring, plays an important role in overcoming these challenges. Depending on the specific circumstances, such monitoring may establish facts that have already occurred (the appearance of karst sinkholes or subsidence, deformation of structural elements of buildings and structures) and/or obtain initial information for forecasting emergencies (recording soil movements, changes in their stress state, levels, and chemical composition of groundwater). For solving operational tasks related to the anti-karst protection of existing buildings and structures, the second aspect is much more important. It should be noted that in our country [XV] and abroad [XVIII], many experts refer to any monitoring of the geological environment that is predictive in nature and carried out in the field of construction as geotechnical monitoring.

Karstological geotechnical monitoring, which involves stationary observations of soil conditions, can be carried out using various methods. After analyzing their advantages and disadvantages, a group of specialists from Nanjing University (PRC) prefers to use underground fiber-optic soil deformation sensors for this purpose [VI]. Unfortunately, the application of this new and highly progressive method faces certain technical difficulties [XVII]. At the same time, practical experience gained over many years in different countries shows that similar tasks can be successfully solved using a more traditional approach – the use of deep marks. For geotechnical monitoring of karst processes, benchmarks were apparently first used (or proposed for use) in the 1960s in the GDR [XI] and South Africa [X]. Various designs of gauges are known that allow recording deep soil deformations resulting from geological processes, including karst processes [IX]. Since karst monitoring only allows for the recording of vertical displacements, it is advisable to limit oneself to installing a system of deep rod marks under the foundation of a building or structure for this purpose. Such systems are particularly effective, firstly, in areas of covered karst, where soluble rocks are covered by a layer of dispersed soils, the thickness of which can reach tens of meters, and secondly, in cases where it is necessary to organize karstological geotechnical monitoring of ground movements at the base of existing construction projects.

The measurement results obtained during any predictive geotechnical monitoring require unambiguous interpretation, and the forecasts based on these measurements need to be verified – both of these procedures can be referred to as the refinement of monitoring systems. If the geological process being observed has not been sufficiently studied, its monitoring must be carried out “blindly.” Fortunately, nowadays this no longer poses a threat to karst monitoring, since the dynamic picture of stress distribution in the soil layer covering the growing karst cavity has been well studied experimentally and has a comprehensive theoretical description [II], which greatly facilitates the task of interpreting the measurement results obtained using depth markers.

It would seem that systems designed for karst monitoring should primarily be tested in areas where karst cavities have been opened up by boreholes, but there is no guarantee that the opened cavity has reached (or is about to reach) a critical state at which noticeable deformation of the overlying soil layer will begin. Using a full-scale experiment for the same purpose, in which an artificial underground cavity is created and brought into an unstable state, is ideal from a methodological point of view, but very expensive and unsafe. As a result, predictive karst monitoring systems have to be tested on laboratory physical models. Despite all the well-known shortcomings of this approach (difficulties in selecting model material, scale effects, etc.), there are examples of its successful application in various countries for developing systems for monitoring karst processes using wells to measure groundwater levels [I], electrical prospecting equipment [IV], and fiber-optic soil deformation sensors [V].

Unfortunately, it is very difficult to find similar examples concerning monitoring systems with benchmarks acting as soil deformation sensors.

There are various approaches to laboratory physical modeling of geological processes. In the field of geomorphology, five such approaches are distinguished [VIII], and in the field of engineering geology, four are distinguished, albeit based on different criteria [VII]. It is believed that in the field of geotechnics, laboratory physical modeling of geological processes with strict adherence to scale can mainly be carried out either in a centrifuge or in a flume using equivalent materials, with both approaches having their advantages and disadvantages [III]. After thoroughly assessing the situation, the authors of the article gave preference to the second approach and chose it as a tool for developing a geotechnical monitoring system for karst processes using depth markers. The decisive factor in favor of this choice was the existence of a previously developed and well-proven technology for laboratory physical modeling of karst processes [XVI]. Three other circumstances were also taken into account, which favorably distinguish tray modeling from centrifuge modeling: lower financial costs, ease of experiment preparation, and the ability to reproduce complex hydrogeological conditions on the model (taking into account the prospect of further research).

II. Materials and methods

The karst monitoring system, which uses bench marks as soil deformation sensors, was tested using equipment designed for laboratory physical modeling of geological processes hidden from direct observation and caused by the destructive activity of groundwater (Fig. 1). This equipment, developed by a group of specialists led by one of the authors of the article, has been successfully used for various purposes, including modeling karst sinkhole formation [XII] and developing a karst monitoring system using electrical prospecting methods [XIII]. For the purpose set by the authors of the article at this stage of research, there was no need to use all the capabilities of the experimental equipment; in particular, aquifers were not specifically simulated, although in the latest experiment, the model material was a water-saturated porous medium.

A total of four experiments were conducted, and in each of them, the working chamber filled with model material simulated the thickness of dispersed soils covering soluble rocks. Fine, uniform sand was used as the model material, which was placed in the working chamber in layers, with each layer compacted, and its properties varied from experiment to experiment (Table 1). The bottom of the working chamber was equipped with double sliding doors, which were used to create a “window” of the required width. It contained a wooden insert, the subsequent removal of which simulated the exit of the karst cavity (the role of which was played by the lower chamber) into contact with the base covering the thickness of dispersed soils.

Table 1. Physical properties of model materials.

Experiment number	Bulk density, g/cm^3	Water content, %	Particle density, g/cm^3	Dry density, g/cm^3	Void ratio	Degree of saturation
1	1.65	9.8	2.65	1.50	0.76	0.34
2	1.62	9.4	2.65	1.48	0.78	0.32

3	1.63	9.3	2.65	1.49	0.78	0.32
4	1.91	19.4	2.65	1.60	0.66	0.78

The lower chamber served as a receiver for the model material in the event of its collapse. The width of the inserts in each of the four experiments was selected so that in the first experiment, when the insert fell into the bottom of the working chamber, a “window” with a width (*b*) of 4 cm was formed, in the second and fourth experiments – 8 cm, and in the third – 12 cm.

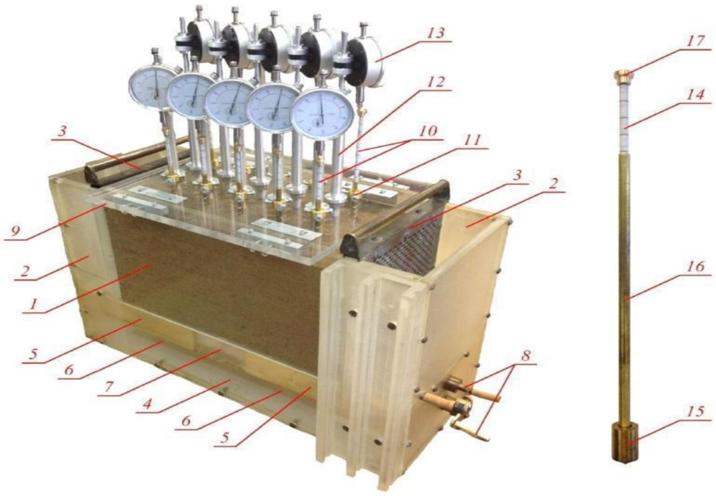

Fig. 1. Experimental equipment: modelling apparatus designed by V.P. Khomenko et al. (left) and benchmark designed by M.M. Utkin and M.V. Utkin (right). 1 – box filled by model material; 2 – side chambers which did not function during considered experiments; 3 – permeable walls; 4 – lower chamber; 5 – upper sliding sections of the box bottom; 6 – lower sliding sections of the box bottom; 7 – dropping insertion; 8 –devices for sliding of the box bottom’s sections; 9 – mounting plate; 10 – bench mark; 11 – bench mark’s fastener; 12 – mounting rod; 13 – dial indicator; 14 – graduated rod of bench mark; 15 – anchor of bench mark; 16 – casing pipe of bench mark; 17 – cap of bench mark.

The monitoring system was reproduced on models using specially designed reduced-size benchmarks (rod diameter 4 mm, anchor diameter 14 mm), the location of which is shown in Figure 2. They were placed in holes drilled into the model material, with the space between the casing pipes and the walls of the holes filled with material extracted during drilling by layering it and compacting it. This is exactly how benchmarks are set in practice. The models, benchmarks, and measuring instruments were installed on a support plate. Each test began with the removal of a weighted wooden insert, which simulated the emergence of a karst cavity of a given width into contact with the base of the dispersed soil layer. The results of the experiments were recorded using measuring scales marked on the benchmark rods and clock-type indicators mounted in their heads. Video recording was performed throughout all experiments.

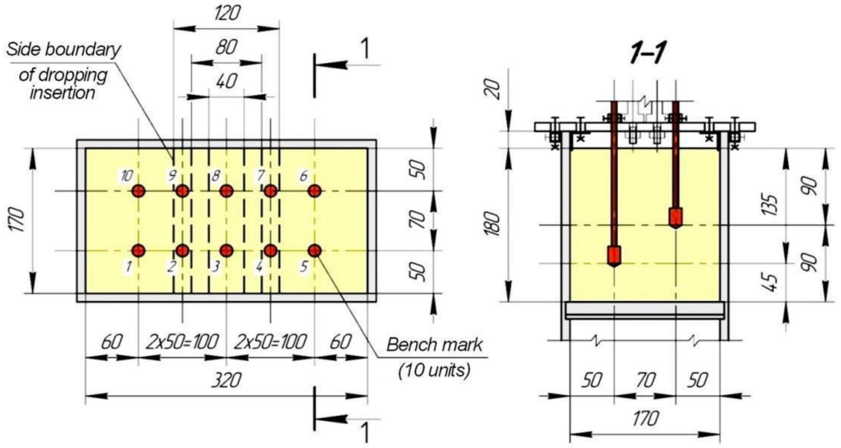

Fig. 2. Disposition of benchmarks in model material.

III. Results

During the first two experiments, after the wooden insert fell out, the model material did not collapse, but during the last two experiments, it collapsed into the lower chamber (Fig. 3). The collapse took the form of internal outbursts, limited by arched vaults, and did not reach the surface of the model material. In the third experiment, the height of such a vault (*h*) was 6.5 cm (h/b = 0.54), and in the fourth experiment, it was 3.5 cm (h/b = 0.44). The following circumstances were noted as the main and fundamentally important results of the modeling.

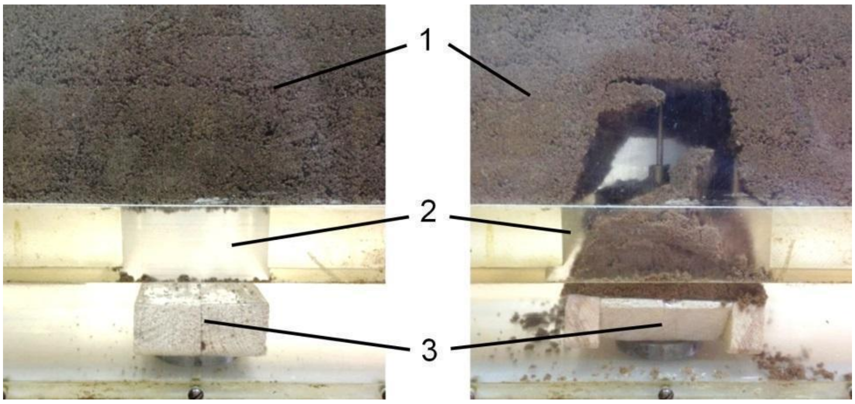

Fig. 3. The results of model simulation of the appearance of contact between a karst cavity and overlapping soil cover during the second experiment (left) and forth experiment (right). View through the transparent front wall of the modelling apparatus. 1 – model material; 2 – “window” in box bottom; 3 – dropping insertion.

1. Benchmarks reacted to changes in stress in the material of the models, although in the first two experiments, their settlement was insignificant and most intense at the moment of insertion, followed, of course, by attenuation. For example, the maximum value of the settlement of benchmark No. 3 in the first experiment was

0.2 mm, and in the second – 1.0 mm. In the last two experiments, the maximum settlement of the benchmarks was much greater, amounting to 45.0 mm in both cases, and was also timed to coincide with the moments when the inserts fell.

2. The deeper the benchmarks settled, the closer their anchors were located in terms of plan and depth to the "window" at the bottom of the working chamber, and the wider this "window" was (Fig. 4). It should be noted that in the first two experiments, no surface sedimentation of the model materials was observed.

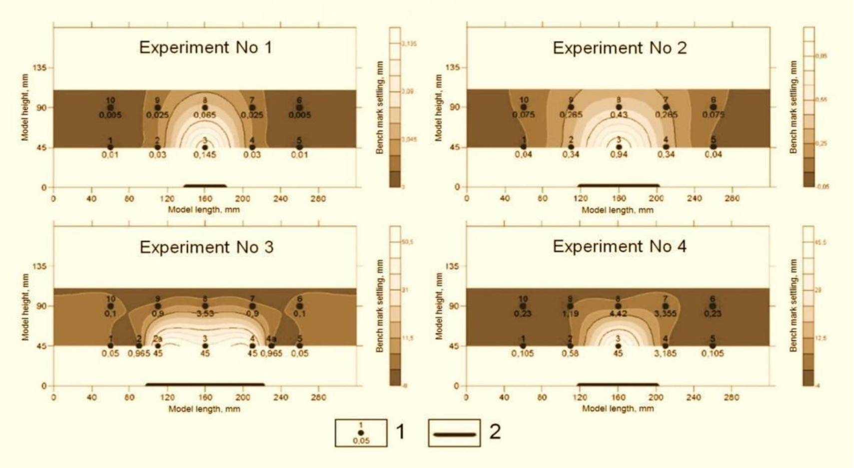

Fig. 4. Benchmarks' settlings which have been registered 30 seconds after "window" appearance at the bottom of the box. 1 – benchmark, its number (above), and its settling, mm (below); 2 – width of "window" in box bottom.

3. The moisture content (i.e., the saturation of the model material with water) had a significant effect on its stress-strain state. For example, in the third experiment (low-moisture material), 30 seconds after the wooden insert fell out, the sediment of the same benchmark No. 8 was 3.53 mm, and in the fourth (water-saturated material) – 4.42 mm. And this despite the fact that in the fourth experiment, the width of the "window" at the bottom of the working chamber was one and a half times smaller than in the third.

4. In the last two experiments, local subsidence formed on the surface of the model material. This was only established by analyzing high-resolution video footage, as the depths of the subsidence were very small. This circumstance once again confirms the fact that, in conditions of covered karst, subsidence of the earth's surface is, as a rule, a kind of predictor of future sinkhole formation. This phenomenon is most characteristic of "simple" and "complex" types of karst-collapse sinkholes [XIV], namely the formation of "simple" types of karst-collapse sinkholes, which was reproduced in models.

5. Physical modeling, which was used to test the karst monitoring system, was carried out on a reduced scale of 1:10 in full accordance with similarity theory. The models reproduced a soil layer composed of plastic sandy loam with a specific cohesion of 11 kPa to 20 kPa and an angle of internal friction of 28° to 32°. However, to solve

the task at hand, an accurate transition to real-world parameters was not as important as obtaining an adequate qualitative picture of the monitoring system's performance.

IV. Conclusion

Modeling has shown that the bench marks of the proposed design allow three tasks to be successfully solved: a) to record deformations developing over time in dispersed soils covering cavities and destroyed zones in soluble rocks discovered during engineering surveys; b) to record similar changes near existing surface karst manifestations; c) to detect secondary cavities and weakened zones in dispersed soils covering soluble rocks, with subsequent recording of their changes over time. All actions necessary to solve the above tasks (as well as any of them individually) can be included in the geotechnical karst monitoring system.

Despite its apparent simplicity, geotechnical karst monitoring using benchmarks as sensors allows for the reliable detection and identification of the first signs of the formation of surface karst phenomena. This makes it possible to take measures for the operational engineering protection of buildings and structures where these phenomena are observed. Such monitoring can become part of a comprehensive system (including, if appropriate, signaling devices) that ensures the safe operation of various types of commercial facilities.

The results of physical modeling presented in the article are only the first step to the development of the proposed karst monitoring system. It is a solely qualitative assessment of its future opportunities. The second step must include the realization of a purposefully planned experimental series with a correct analysis of its results. Only after that, a possibility will arise to compare experimental results with analytical or numerical solutions.

V. Acknowledgments

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Conflict of Interest:

The authors declare that there is no conflict of interest regarding this article.

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