Applied Sciences Research Periodicals
February 2024, Vol. 2, No. 2, pp. 16-20

Basics of Modern Methodology of Research of Geotechnical and Hydrogeological Systems

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In the second half of the 20th century, significant changes have taken place in the general scientific methodology, which are connected with the awareness by specialists of the non-linearity of all processes in the surrounding world. As the technical and technological capabilities of scientific research developed, which allowed scientists to penetrate more deeply into the essence of the researched processes and phenomena, it became clear that linear ideas about the development of natural objects (systems) were increasingly unable to explain the inconsistency of the new scientific facts of the theory. A scientific revolution was ripe, which required the formation of new paradigms, approaches, and principles of scientific research. As a result, starting from the 60s of the XX century, new scientific directions based on the concept of nonlinear dynamics began to develop rapidly. The generalization and the result of the rethinking of the paradigms of classical science became the general scientific synergistic paradigm, which absorbed the latest scientific achievements in the field of systems theory, information theory, nonlinear thermodynamics, cybernetics, nonlinear mechanics of continuous medium, etc.

Scientific innovations and earth sciences, in particular - geotechnics and engineering hydrogeology, were not bypassed. The peculiarities of these sciences, namely the impossibility of observing the development of geosystems in real-time, the professional inertia and unpreparedness of geologists, geotechnicians, and hydrogeologists in general to understand the synergistic paradigm, which in a certain way inhibits its use in research practice. Today, the efforts of scientists in the fields of geotechnics, engineering geology, and hydrogeology are aimed at realizing and implementing the synergistic paradigm in theory and practice. It is essential to acquaint construction and nature management specialists with the basic provisions of synergy and information theory about the problems of geotechnics, and related sciences with some new approaches in relevant research.

SYNERGETICS OF THE DEVELOPMENT OF HYDRO GEOTECHNICAL SYSTEMS

Synergetics *(from the Greek συν - a prefix with the meaning of commonality and ἔργον - activity, action)* is the science of interaction and self-organization in systems of various nature. It studies phenomena and processes, resulting in which properties may appear in the system, which may not be present in any of the parts. The identification and use of common laws in various fields requires interdisciplinary cooperation - cooperation in the development of synergy of representatives of various scientific disciplines [1].

The synergetic paradigm formed at the end of the XX century fundamentally changed scientific phenomena about the development of the surrounding world. First of all, the synergistic approach will be of interest to scientists who study real-time systems. In Earth sciences, the situation with the introduction of the synergistic paradigm is significantly different. So, in geology, the objects of research - geosystems - develop on a geological scale, and the characteristic period of development of geological processes is approximately 10^6 - 10^8 years. As a result, geological structures (geosystems) represent modern people as static and are studied only as sources of structural information that has developed today. The tool for studying the dynamics of geosystems is, mainly, hypothetical conceptual models that find partial confirmation in the results of field research. Therefore, the interpretation and research of the possibilities of applying the principles of synergy in the studied geosystems is not only an important theoretical but also a relevant task.

Synergetics as a science appeared in the middle of the 20th century thanks to the fundamental research of the German scientist H. Haken [2-4]). In the mid-60s, he formulated the basic principles of synergetics as a science of interaction and self-development of large complex open systems. This research was facilitated in the first half of the 20th century by developments in system theory by A. Bogdanov and L. Bertalanfi, in cybernetics by N. Wiener, in information theory by R. Hartley and K. Shannon, in thermodynamics of non-equilibrium processes and systems, by I. Prigozhin and co-authors [5-6] and other researchers. An important methodological consequence is that I. Prigozhin [7] substantiated the information criterion of the evolution of systems, which allows for considering their development as a continuous process of accumulation and transformation of information.

Modern synergetic as a science of self-development is based on two fundamental propositions that are not characteristic of classical science. This is the nonlinearity and unpredictability of the processes of evolution in complex systems and the emergence of regimes with exacerbation (rapid avalanche-like growth). Today, the synergistic approach is increasingly being used in geology and related disciplines, because synergistic principles and patterns of self-development of large complex systems certainly extend to geosystems as well.

The main process in hydrogeosystems is fluid filtration in voids and cracks of water-bearing rocks. Therefore, their most important feature is that they, as secondary formations in relation to primary geological structures and manmade geotechnical formations, are more dynamic, change much faster, and their evolution is available for observation and research for several or tens of years. Another feature of hydrogeosystems is due to the fact that all types of their regime (hydrodynamic, hydrochemical, hydrothermal, and others) are well formalized and described by appropriate equations, which allows the use of mathematical models for their research. In addition, the regime of hydrogeosystems is easier to control, that is, you can experiment with their dynamics.

As it follows from the research of the scientific school of I. Prigozhin, the development of any large complex and open system depends on the degree of its imbalance. When the system is in a state of complete equilibrium, there are no drains and sources in it. This means that there are no gradients and flows of matter and energy within the system and between it and the external environment, and the total entropy reaches its maximum value. In the hydrodynamic interpretation, this means that there is no gradient of gravitational potential (pressure) and flow (movement) of groundwater in the hydrogeosystem. Water particles (aggregates of molecules) in the pore space can move chaotically only under the influence of molecular interaction forces. After the system is brought out of equilibrium, substance and energy gradients arise between it and the external environment, as a result of which the material-energy and informational exchange within the system and with the environment begins. In a slightly unbalanced state (in the region of homeostasis), these flows have a linear reversible character, fluctuations of system parameters under the influence of the external environment are suppressed by negative feedback mechanisms, as a result of which the system maintains a certain constancy of structure and functioning with a minimum of entropy production.

With regard to the hydrogeosystem, it should be noted that the appearance of a pressure gradient in it due to a change in the external environment begins to affect the processes of molecular interaction between water and rock particles in the pore space. In voids of a sufficiently large size, the gravitational movement of water begins with a minimal pressure gradient. In finer pores, if there are a large number of clay particles in the granulometric composition of the soil, the structural viscosity of water, due to the sorption potential of the soil, first appears. The movement of water in them begins with the achievement of some initial pressure gradient sufficient to overcome the forces of molecular interaction. And only after that, a laminar flow of groundwater is formed in the entire space of the hydrogeosystem, which is described by Darcy's linear filtration law. The structure of the flow depends on the specific characteristics of the primary geological structure of the hydrogeosystem, or the artificially created geotechnical system and hydrodynamic features at the boundaries of the system. At each point of the flow, the velocity vector is stable in direction, and its length depends on the magnitude of the pressure gradient. This is the constancy of the hydrodynamic structure of the flow and hydrogeosystems as a whole.

In a more unbalanced state (near the border of the homeostasis region), the material, energy and information flows in the system acquire a non-linear character and are described by non-linear equations. As a result, positive feedback mechanisms that contribute to the accumulation of fluctuations (mutations) in the system begin to manifest themselves. In a strongly unbalanced state (far from the state of equilibrium), the action of positive feedback mechanisms prevails, as a result of which fluctuations are not suppressed, but accumulate. When they reach critical values at bifurcation points in a state of instability, the system undergoes a phase transition, i.e., jumps into a new state - new structure, properties, behavior, functions, etc. are formed. In the hydrogeosystem, the increase in instability leads to flow turbulence, when the velocity vector at any point begins to pulsate - to randomly change direction and length. Such a flow regime is described by a binomial dependence of the filtration rate on the pressure gradient with a predominance of the quadratic term. In this case, suffusion may occur in well-permeable porous rocks, as a result of which not only the mesostructure of the groundwater flow changes, but also the lithological composition and geotechnical characteristics of water-bearing rocks change irreversibly due to the removal of small particles. Thus, beyond the region of homeostasis (linear flow regime) irreversible changes occur in the hydrogeosystem, which in a degenerate case can lead to its complete destruction. At the same time, in the zone of influence of such a hydrogeosystem, engineering structures (for example, dams, buildings, etc.) may partially or completely lose their stability and collapse due to violations of the foundation.

Often, at the point of bifurcation, there are many possible options for the further development of the system (new states), from which the most probable one is "chosen" at random. Further, the system continues development according to the "selected" option to such a bifurcation state. Thus, the development trajectory of non-equilibrium systems is a sequence of bifurcation points in which a revolutionary leap-like phase of development is realized, and between them - a calmer evolutionary one with the gradual accumulation of new properties. Therefore, if a large number of strong parameter changes accumulate in the evolutionary phase of development, at the next bifurcation point the system may move into the area of attraction of another attractor (Eng. attract - a set of points in the phase space to which the phase trajectories of the system's movement coincide). This leads to a radical change in the direction of development. In addition, specific order parameters are formed at the higher hierarchical levels of the system, which determine its behavior and properties at the macro level, as they have a much greater influence compared to the operating factors of lower hierarchical levels. As a result of the stochastic nature of the behavior of the non-equilibrium system at the bifurcation points, forecasting its development as a whole becomes problematic.

In the 70s of the last century, I. Prigozhin showed that in strongly unbalanced states of the system, another new invariant of development appears - as a result of self-organization, dissipative structures are formed, which are highly resistant to environmental disturbances. In hydrogeosystems, apparently, dissipative structures are formed locally in karst cavities, crack systems with large openings, etc., where the resistance to the movement of groundwater is minimal and the energy of the flow is spent not only on movement, but also dissipates due to the intensive mechanical mixing of flows and the formation of a free surface.

It can be seen from the above that in the subject-object area of engineering geology, hydrogeology and geotechnics, one can find confirmation and methodological possibilities of applying the main provisions and principles of synergy in the study of hydrogeotechnical systems [8-9]. However, one important feature of the functioning of hydrogeosystems should be noted: all of them, almost without exception, at different hierarchical levels, experience the effect of a powerful universal parameter of order - human influence. In some cases, this influence is targeted, and then we can talk about the management of hydrogeosystems (drainage, water intakes, replenishment of reserves, optimization of the regime, etc.). In others, it manifests itself as an unpredictable result of nature management (desertification or, on the contrary, flooding, landscape change, subsidence of the earth's surface, deterioration of the quality of groundwater, depletion of aquifers). In the first case, the hydrogeosystem development attractor (the goal of development) is specifically set by society, and in the second case, it is formed by chance as a result of a person's inability to foresee the negative consequences of nature use. This is precisely the need to take into account synergistic effects in the development of hydrogeosystems in order to better understand the mechanisms of minimizing or completely eliminating the negative consequences of managing not only hydrogeosystems, but also natural systems as a whole.

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