EARTH SCIENCES

ENHANCED APPROACHING TO THE ESTIMATION OF SUBSOIL POLLUTION RISKS WHILE OIL DEPOSITS DEVELOPMENT

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Abstract

One of the main environmental risks associated with oil field development is the spill and squizing of polluting liquids on the surface and in the subsurface space (hydrodynamic processes).

As a result of the combined (external and intra-layer) impact, the surrounding porous and permeable medium goes into an unnatural state of microstresses (destructive state). The filtration properties of such a medium (porosity and permeability) are determined by the number of cracks per volume and the specificity of fluid movement in pores/cracks. This article analyzes issues related to the formation of a crack system in stressed solid media from the standpoint of fractality. In particular, the process of crack formation and its relationship with the average fractal number (fractal dimension) are explained.

Keywords: subsurface pollution risk, fluid movement in fractured environments, fractal dimension of the fracture system in subsurface environments.

I. INTRODUCTION

The most well-known environmental risk of subsurface pollution during oil production is the spill or seepage of petroleum liquids into the soil (Fig. 1, 2). When transporting oil or oil products from under technical structures, such as oil fields, oil pipelines (onground, underground, underwater), storage facilities, etc., pollution can spread to subsoil levels and groundwater, threatening the poisoning of drinking water and the destruction of ecosystems.

Another significant environmental risk of subsurface pollution during oil production is the use of process fluids and chemicals in the oil productions..Improper use or leakage of these chemicals can lead to contamination of the subsurface environment and groundwater. Some of these chemicals can be toxic and negatively affect animals and plants, as well as people who may be harmed by contaminated drinking water or food.

Naturally, there are effective measures to manage and reduce the risks of subsurface contamination in oil production, including strict control and proper operation of technical structures, the use of modern technologies and equipment to prevent leaks and spread of petroleum products, and the use of environmentally friendly chemicals and methods.

However, the implementation of all these measures does not exclude regular monitoring of the condition of the soil, groundwater and ecosystems, both the adjacent territory and the technical infrastructure of oil fields, which is necessary for the rapid detection and elimination of any contamination. Proper planning, risk assessment and adherence to strict safety measures will help minimize environmental risks in oil production.

Practical assessment of the dynamics of changes in the level of soil pollution during oil production, in addition to monitoring, can also be carried out using a number of specific methods and tools, for example, the use of geophysical methods (electromagnetic or seismic) designed to determine changes in the structure of the soil due to pollution.All these methods allow for a systematic assessment of changes in the level of pollution during the oil production process, which in turn makes it possible to develop the necessary measures for the cleanup and remediation of contaminated areas.

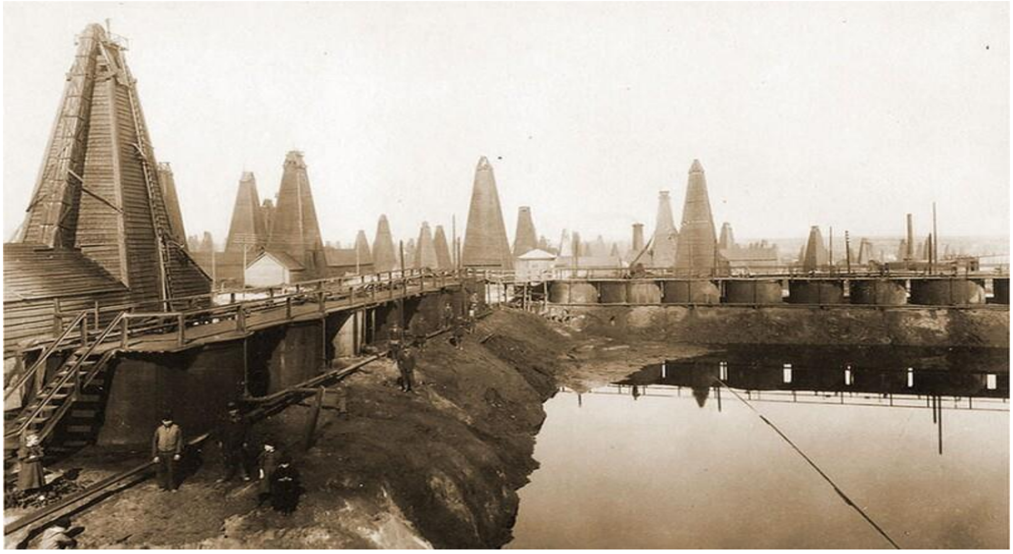


Fig. 1.
Crude oil and waste contained in a pit next to production wells at the Balakhani oil field in (Baku, 1900–1917).

It should be understood that the reliability of the applied methods for assessing the level of soil contamination during the oil production process largely depends on the size, structure and shape of the pore space distribution of the surface and subsurface layers of the oil production area. In this sense, the concepts of the fractal structure of the distribution of pore space in oil-containing rocks are quite well known. In particular, it is believed that the fractal structure of the distribution of pore space in oil-bearing rocks is one of the key characteristics of geological environments that determine permeability and oil saturation in reservoirs.However, this structure has a variety of sizes, geometric shapes and complexity of organization, which makes its study difficult and ambiguous. Thus, a fractal is a

mathematical object that has unusual properties of self-similarity. In the porous structures of sedimentary rocks, fractality is a reflection of various physical processes occurring at different stages of formation. In other words, the natural porosity and permeability of the environment (or reservoir capacity) can be successfully determined from the position of fractality.

Fig. 2. Industrial oil production in Azerbaijan in the middle of the last century on land (Bibi-Heybat) and at sea (Oil Rocks).

Studies and experiments are known from the literature, have revealed the main patterns of the fractal structure of pore space in sedimentary matters. At the same time, important factors influencing this structure have been identified, among which the key ones are the genesis of the rock, the material composition of the sedimentary matrix, thermo-geological conditions and pressure in the earth’s crust, as well as the age of formation of the rock. On the other hand, the fractal structure of the pore space of reservoir rocks also has a significant impact on the processes of oil movements. Firstly, it determines the effective surface area of the pore space, which reflects the volumetric oil content and adsorption-dispersion processes in the pores. Secondly, the fractal structure affects the mechanisms of oil migration in porous media, on which the speed and efficiency of oil penetrations significantly depend.

II. RESEARCH METHODOLOGY

In general, studying the fractal structure of the pore space makes it possible to improve the representation of the geological model of the field, optimize oil production processes and, associated with this, environmental pollution. The latest methods and technologies based on the principles of fractality make it possible to predict and simulate the distribution of reservoir properties of the environment and ensure total efficiency, as well as environmental safety of oil production

However, along with the natural fractal structure of the pore space of oil-bearing reservoirs, the technology of downhole operations for hydraulic fracturing (HF) and other methods of processing productive formations is widely used in oil production practice. The use of hydraulic fracturing technology, even with the most favorable natural hydrodynamics of the movement of intrapore fluids, is usually aimed at increasing the efficiency of oil and gas production, as well as improving the recovery rate of reserves.

Thus, as a result of artificial in-situ hydraulic fracturing in oil-containing medias of the deposit, in-situ "corridors" for water movement additionally appear, making it difficult for oil to seep through the initially branched network of natural cracks. In other words, the hydraulic fracturing technique (HF) leads to the destruction of the original natural structure of the pore space of medium containing hydrocarbons.

At the same time, natural oil-bearing porous and cracs pass into a secondary intermediate (destructive) state, which is characterized by the density of cracks per unit volume of the medium (fractal) [1, pp.30–35; 2, pp. 11–31]. This volume can have an arbitrary size (1 m3 or 1 cm3) and has an certain number of cracks, or an unlimited number of cracks. The classic term "fractality" implies the fragmentation of the solids media (rocks) by a network of cracks (Fig. 3). In extreme cases, the porous structure (fractal, fragment) of media may not contain any cracks, and in completely disintegrated condition it pass to the state of loose sand.

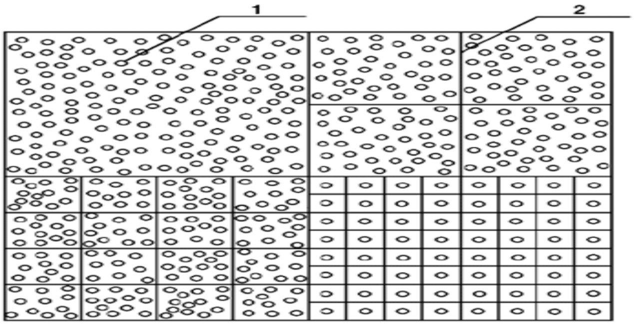


Fig. 3. Fractality of a porous reservoir.
1, 2 – levels of fractality (density of cracks per volume)

It is known that in nature, the process of cracking in solid media occurs under the influence of geostatic, tectonic, etc. stresses, leading to local deformations of the environment. Moreover, deformations of natural geological environments have a specific character and, as a rule, develop according to a nonlinear law. The traditional Hooke's law of deformation (F = – k*X) usually is valid mainly at the initial (linear) stage of the deformation process. In other words, when the deformation increases to a certain threshold value, the linearity of the deformation process is disrupted and a redistribution of individual components of the general stress field occurs (breaking of elementary particles' bonds).

As a result, a branched (secondary) system of cracks appears in the solid matrix. The process of the described deformation is quite common in nature and is similar to both tensile and shear deformation. It was found that the configurations of secondary cracks in both cases are very characteristic and have a pronounced fractal structure (Fig. 4) with a dimension of 1.62 – 1.64.

The above-described process of fractal cracking in solid geological media illustrates the unpredictability of the direction of crack development, and the similarity of the fractal dimensions of crack systems under tensile and shear deformations confirms the impossibility of determining the types of external load based on the predominant direction of cracks.

Modeling the general development of a system of faults (cracks) as a result of loads is as follows. At the initial stage of loading, individual chaotically oriented cracks appear in the medium (Fig. 5, a). Further, during subsequent loading stages, these cracks begin to merge (Fig. 5, b). As a result, a single fault area (plane) is formed (Fig. 5, c).

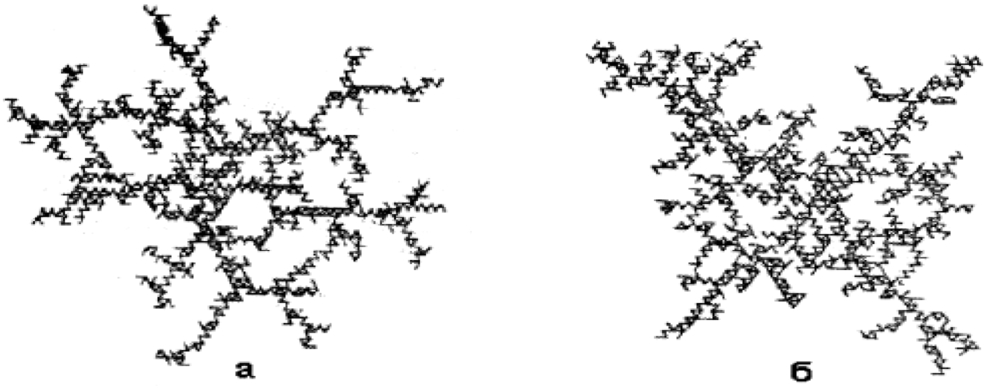


Fig. 4. Fractality of cracks under different types of deformation:
a – tension, b – shear [1, pp. 30–35]

III. RESULTS AND DISCUSSIONS

The identification of the presence of a connection between the above-described process of crack formation and the values of the corresponding fractal dimension is proven by assessing the variation in the values of the fractal dimension of the system during the formation of secondary cracks [3, pp. 10–14]. However, since this is practically impossible to do in real time, the entire process, with a certain degree of reliability, can be adequately modeled in the following sequence.

Let us assume that a certain square area of size axa of some surface is divided into n elementary areas ΔS, each of which is formed by four rods forming 4 sides (Fig. 6). The figure shows an elementary platform ΔS, each side of which is a side of the adjacent platform and has its own ultimate strength Pi j.

Further let us assume that a force F is applied to the middle of the selected area axa along the line (0,a/2; a,a/(2)), which linearly decreases from the value of F on the line (0,a/2; a,a/(2)) to 0 at the edges of the area, that is $F = F - \left(\frac{2}{a} \cdot i\right) \cdot F$

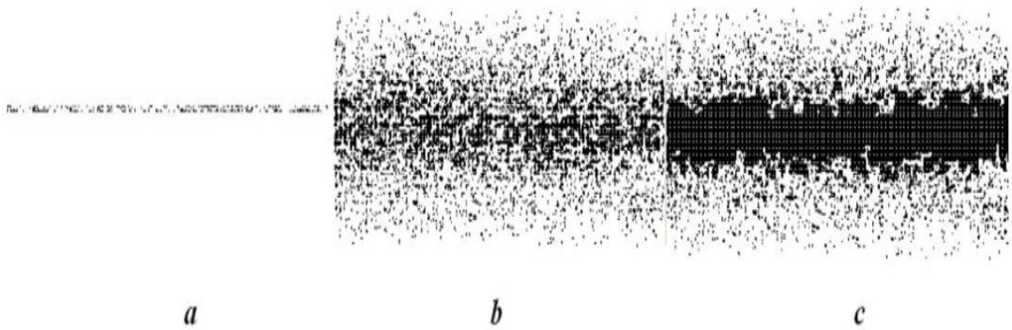


Fig. 5. Development of a system of fractal faults during loading [3, pp. 10–14].

It is obvious that, according to the conservation law, the force acting on the area (Sij) is determined by the formula (Fi = F1,i+ F2,i+ F3,i+ F4,i), where F1i, F2i, F3i, F4i are the forces acting on the sides of the platform (Sij). Here it is appropriate to assume that

(F1i = F2i = F3i = F4i = F/4).

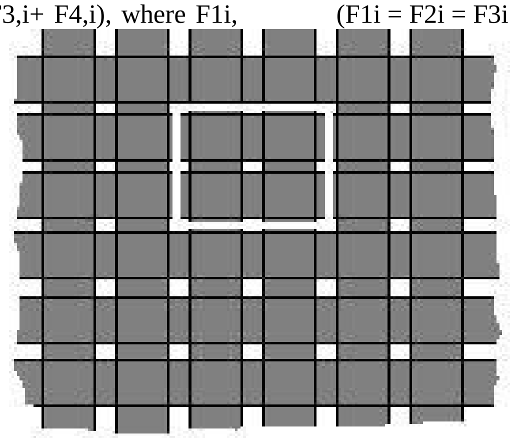
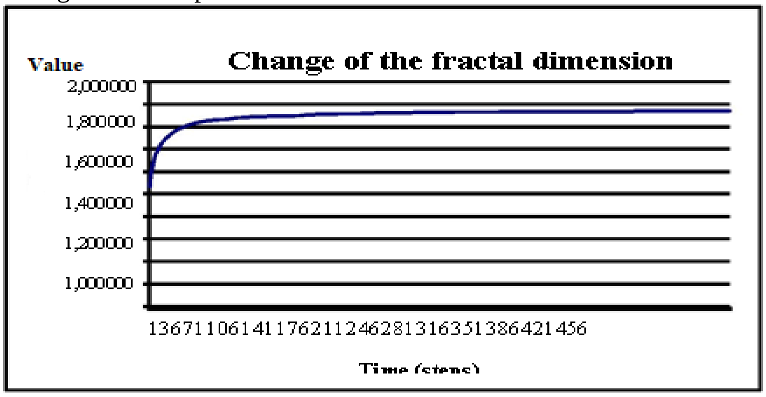


Fig. 6. Elementary area ΔS [3, pp. 10–14].

For the numerical calculation, we take the dimensions of the site equal to 240x240, and the value of the strength limit Pij was set using a random number generator at Pij<1 (force F=1). When the load Fij>Pij is reached, the site side ΔS is destroyed.

Calculations show that the fractal dimension of the system during the process described above increases from 0 to 1.75, and the increase in fractal dimension in the first stages of the process occurs quickly, a chaotic system of cracks is formed, with a fractal dimension approaching a value of 1.6. Subsequently, the cracks begin to unite and form a rupture area.

Here the fractal dimension grows slowly, starting from 1.6 to 1.73. After this value, the fractal dimension of the system, during subsequent modeling steps, remains practically constant (Fig. 7).



Pic.7. Change in the fractal dimension of the system during the experiment [3, pp. 10–14].

In this case, the collapse of the sides of elementary square platforms is concentrated in the direction of action of force F. At the completion of the formation of the rupture plane, an area is formed that is a fractal cluster, including the entire chaotic system of cracks. During this stage, the fractal dimension increases slightly to 1.75, but no new destruction is observed.

Characterizing this process from the perspective of energy exchange, it can be noted that during of the elastic cracking, over time, the total energy of the system begins to decrease monotonically, i.e. the more the cracks grow, the more stable the system becomes. Therefore, it is quite natural that when the energy is exhausted, the growth of cracks stops.

This means, according to the results of calculating the increasing of the destruction zone, it is can say that the value of the fractal dimension as a quantitative criterion can well be used in diagnosing the processes of self-organization of fractured systems

However, natural geological environments are usually characterized by a certain multi-level heterogeneity of texture (structure) and defects at various hierarchical levels [4, pp. 507–528; 5, p. 21; 6, 357 p., 7, pp. 289–305]. In this regard and also taking into account random fluctuations in the distribution of micro- and macro stresses on the noted inhomogeneities, obtaining the specific characteristics of geometrically identical samples of the medium revealed that, along with factors confirming the similarity law, significant deviations from this law are also observed.

Consequently, given that the observed deviation is a consequence of the geometric dimensions of solid deformable bodies, the reasons for this deviation can be associated with the scale factor, and the phenomenon itself is called the scale effect [8, 151 p.; 9, pp. 87-96; 10, pp. 46-53; 11, 23 p.]. In particular, for a continuous closed curve γ, characterized by the properties of homogeneity and self-similarity, a power function is valid [12, 254 p.; 13, pp. 19-26; 14, 47 p.]:

$$L\eta = \lambda\, \eta^{1-D}$$

here Lη is the length of the broken line approximating this curve, composed of segments of constant length η.

For cases when D>1, the curve is a fractal. In this, the homogeneity of the curve means that all sections of the function between adjacent vertices of the approximating broken line with links of length η create an equal number of segments on the approximating broken line with links of length ξ<η, and the property of self-similarity is reflected in the similarity of the curve in any part of it. Thus, the number of segments of a broken line with a link length ξ that fit between adjacent vertices of a broken line with a link length η depends only on the value of the ratio η/ξ, but not on the values of η and ξ separately.

In other words, moving from geometric images to the physical objects they represent, one can easily establish fractality using the parameter η/ξ.

IV. CONCLUSION

The reliability of the applied methods for assessing the level of soil contamination during oil production, which depends, to a large extent, on the size, structure and shape of the distribution of the pore space of the surface and subsurface layers of the oil production area is substantiated.

The process of deformation of porous and permeable reservoirs with the formation of a branched system of cracks with a fractal structure is considered. In particular, using an experimental and theoretical example, a model of the relationship between the cracking process and a change in the fractal dimension of the system is presented, according to which, at the initial stage of cracking, a chaotic system of cracks appears, accompanied by an increase in the fractal dimension of the system to a value of 1.6. At the next stage, with a slow increase in fractal dimension from 1.6 to 1.73, the cracks begin to unite and form a rupture area. Further, the fractal dimension practically does not change and, when the value reaches 1.75, a break in the continuity of the medium occurs.

Applying the presented method for assessing the distribution of natural porosity and permeability (or Filtration and Capacitance Properties - FES) of the surface and subsurface parts of the soil from the position of fractality, it is possible to minimize environmental risks during oil production and will gain greater efficiency and reliability, more close to natural.

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