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MAIN GEOCHEMICAL ISSUES OF RELEVANCE TO GAS PRODUCTION AND UNDERGROUND STORAGE OF OIL AND GAS

Prepared by the delegation of the Russian Federation

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1. The development of gas, gas condensate and petroleum deposits and the construction and operation of underground oil and gas storage facilities, like any mining operations, are accompanied by changing stresses, deformation and displacement of the surrounding and overlying rock mass, i.e. by geomechanical processes. Geomechanical processes put additional operating loads on borehole structures and lead to the formation of highly permeable and fractured zones (i.e. additional fluid flow channels) in the rock mass, and displacement of the Earth's surface. The nature and intensity of geomechanical processes largely determine the environmental and industrial safety of extraction facilities and the underground storage and transport of raw and processed hydrocarbons.

2. When addressing the tasks in geomechanics that arise during gas, gas condensate and petroleum extraction and underground storage of gaseous and liquid hydrocarbons, it is advisable first to dwell on the differences between geomechanics and geodynamics, because it is clear that, in the last decade, these two words have been interchanged, whether intentionally or otherwise.

3. Geodynamics is the science of deep processes that occur as a result of the evolution of the Earth as a planet and determine the movement of matter and energy inside the Earth and within its crust. These deep processes cannot be studied directly, and conclusions about their nature can be drawn only from their manifestations in features of the Earth's crust that are situated close to the surface, using various universal theories, ideas and hypotheses (for example, the hypothesis that continents are static and the opposing theory of continental drift, which lead to different interpretations of the manifestations of deep processes). When geodynamics is mentioned in relation to mineral extraction, then the field referred to is usually regional geodynamics - the study of the interaction between lithospheric plates and the results of its manifestations at specific parts of the Earth's surface. Even in this narrow field, however, the interpretation of geodynamic manifestations and, what is particularly important, their prediction, are not possible without universal theories.

4. Unlike geodynamics, geomechanics studies the processes of deformation and degradation of rock and rock masses resulting from the impact of human activity on the subsoil during mining and the construction and operation of various underground facilities. Geomechanics focuses on the rock mass that is adjacent to the underground facility, or is displaced during mining or operation of an underground storage facility. Thus the extent of the rock masses examined in geomechanics can reach several dozens of kilometres, while regional geodynamics studies areas of the Earth's crust thousands of kilometres and more in size. Geomechanics is closely linked to geology and engineering geology, geophysics and other earth sciences. Whenever possible it uses, as initial data, the results of geodynamics research, for example data on current stresses as in rock masses in various regions of the Earth. In turn, geodynamics uses the results of geomechanics research, for example data on the stresses in a rock mass, collected by conducting hydrofracture tests in boreholes. In addition, geomechanics is linked to technical disciplines - the techniques for exploiting deposits, constructing and operating underground facilities, and engineering mechanics. Since geomechanics takes production factors into account, it is a wider discipline in this respect than geodynamics, but is inferior to it in terms of the scale of the objects examined because it studies local areas of rock. Thus, although geomechanics and geodynamics are closely related branches of science, the tasks they set and resolve are different.

5. What scientific and technical tasks, related to the development of gas, gas condensate and petroleum deposits and the underground storage of oil and gas, can and should geomechanics resolve?

(a) The first, and one of the main, scientific and technical tasks in geomechanics is the quantitative evaluation of the mechanical characteristics and initial stresses in a rock mass, including oil-, gas- and water-bearing strata, which must be used as initial data for all subsequent tasks linked not only to geomechanical but also to hydrodynamic and gas-dynamic processes. Ideally, the three-dimensional distribution of the characteristics and state of the rock within a mining area should be known before a deposit is developed or an underground facility constructed. The main difficulty with this is the impossibility of making this type of evaluation for a rock mass in its initial (undisturbed) state: the mechanical characteristics of rocks are currently determined under laboratory conditions using core material, and the only direct method of evaluating the initial stresses in a rock mass is the borehole hydrofracture method. Thus, both cases involve the drilling of boreholes, which leads to a redistribution of the existing pressures in the rock mass, and to deformation and degradation processes that can alter the state and characteristics of the core and the rocks near the borehole walls. Therefore, a reliable evaluation of the characteristics and state of a rock mass requires both new methods of determining the characteristics and state of rocks in an undisturbed rock mass, and better ways of interpreting the results obtained with existing methods, taking into account the geomechanical processes that occur when prospecting boreholes are drilled.

(b) Another task in geomechanics is to predict and ensure borehole stability. In this case, stability is used in the extended sense, meaning, that the underground structure should keep its operational characteristics for the prescribed period of operation. This is an issue from when boreholes are first drilled, a process which, as mentioned above, is accompanied by a redistribution of pressure in the rock mass and the deformation and degradation of the borehole walls and adjacent rock. Depending on the characteristics of the rock, the state of the rock mass and the properties of the drill mud, deformation and degradation may manifest themselves in the formation of cavities in borehole walls, borehole ovalization and flooding, and the appearance of cracks in the walls as a result of hydrofracture, which will adversely affect drilling, technically and economically, and make, later, for unsatisfactory cementation quality and other undesirable consequences, up to and including accidents. One means of controlling the state of the borehole walls and adjacent rock when drilling is to select drill mud of appropriate density. Simply increasing the density of the drill mud does not solve the problem because in addition to economic aspects (density “grams” are not cheap), there are also technical considerations requiring the use of drill mud of the lowest possible density (drill mud circulation, drilling productivity, the possibility of losing high-density drill mud in hydrofracture cracks, etc.). To select drill mud of optimal density for a given depth (i.e. the lowest density will keep the borehole stable) the likelihood that the borehole walls and surrounding rocks will disintegrate, and how, must be predicted, which can be done using geomechanical calculations.

6. The stability (including tightness) of the lined portion of a well during the exploitation of a deposit or the operation of an underground storage facility is determined by the quality of the cementing around the casing-string borehole annulus and the properties of the cement stone, the characteristics of the casing pipe, and the type and intensity of the load upon the bore lining consisting of the casing string and the cemented ring. The quality of the cementing, which largely depends on the stability of the open well-bore during drilling, can be improved by using

special plugging techniques (e.g. continuous casting with vibration compacting) and a suitable choice of plugging materials and agents offering the requisite gripping and thickening times and a plugging solution of the right viscosity. The choice of design for the casing string (typical sectional dimensions and length of casing pipes, types of threaded joint) and composition, in terms of mechanical strength and adhesive properties of the cement stone, of the plugging solution, is based on the nature and intensity of the load on the bore lining; this depends on the effects of the internal pressure, normal and incidental external loads, and the axial loads imposed by the weight of the casing string itself. The magnitude of the external loads, both in the plane perpendicular to the well axis and along the axis, can be determined by geomechanical analysis of the displacement, deformation and destruction of the rock mass, which are also affected by the regime under which the deposit or storage facility is operated. The geomechanical task of forecasting and ensuring borehole stability is significantly harder when the well axis is inclined away from the vertical or when pore pressures or temperature gradients are anomalously high.

7. The next task is concerned with the mechanical conduct of oil-, gas- and water-bearing strata when fluid is extracted from or injected into them. Such strata consist of a consolidated or unconsolidated porous medium subjected to loading, with significant variations in pore pressure, as a result of the extraction or injection of fluid. The loading leads to stresses in and deformation of the rock skeleton and general deformation of the stratum, displacing the overlying rock and deforming the land surface. Loading and deformation of an oil-, gas- or water-bearing stratum is accompanied by changes in their fluid-bearing properties (porosity, permeability, etc.) over the length and depth of the stratum. Hence the technological operating parameters of a deposit or an underground storage facility in an oil- or gas-bearing stratum (pressure, extraction and injection volumes, well flow rate and so forth) are directly related to the geomechanical processes of deformation in the stratum, which may change elastically or inelastically depending on the load on the rock skeleton. Studying these processes is therefore essential not only to forecast displacement in the overlying rock and deformation of the land surface but also to forecast the operating parameters of the deposit or facility.

8. Increasing flow rate by boosting fluid flow is another task in this category. One means of boosting fluid flow to the well bottom is hydraulic fracturing of the rock formation or one of the variations thereon (multiple, directional, etc.). The same applies when methane is extracted from coal seams, since hydraulic action on the seam by creating fracture systems of specified extent and orientation is the principal means of increasing methane yield.

9. Changes of varying intensity in the deformation and displacement of the overlying rock burden and land surface accompany the exploitation of a deposit or operation of an underground storage facility. Sundry variations in the geomechanical processes of overburden displacement and deformation are possible:

- If the fluid-bearing stratum consists of dense, rigid rock types such as hard sandstones, limestones or dolomites, it will undergo slight elastic deformation resulting in small changes in seam thickness (from a few centimetres to a few decimetres) which, when the sections of rock mass subject to displacement are extensive, will not lead to any significant subsidence or deformation of the overlying rock mass or land surface, although it may permit fluid to migrate to higher strata even so. This is very likely what is being observed at the North Stavropol gas storage facility;

– If the fluid-bearing stratum consists of poorly cemented rock such as sands, friable sandstones or dense silt, deformation may be significant and seam thickness may change by as much as several metres. In this case subsidence and deformation in the overlying rock will be substantial, especially at the fringes of the reservoir, and may be accompanied by rock slippage along stratum layers - which can be extremely dangerous for wells under exploitation - and the appearance of areas of higher permeability and failure cracks. The deformation at the land surface may pose a risk to buildings, structures, technological plant and environmental protection installations above the area being worked;

– If the fluid-bearing stratum consists of dense, rigid rock but the overburden contains layers of rock that has not fully compacted and is initially under high fluid seam pressure (e.g. relatively impermeable waterlogged clays), even small deformations of the fluid-bearing stratum may create substantial displacements of the rock mass being worked and of the land surface above, as fluid migrates out of the uncompacted rock into the drained reservoir and the rock then contracts. The uncompacted rock may contract by as much as several metres, and this contraction may be accompanied by land settlement of a similar magnitude. Just such a mechanism of land displacement and deformation has been observed at several oilfields in the United States of America, and also at one North Sea field;

– If the rock overburden is broken into blocks by systems of cracks (contains fracture failures) it may shift and deform dynamically, which will be manifest in the form of man-made seismic events - human-induced earth tremors brought about by the activation or development of existing faults and individual blocks moving against each other along the fault lines as fluid is extracted or injected. Human-induced seismic activity at various scales has been observed on many occasions, during the exploitation of oil fields (Goose Creek, Wilmington, Buena Vista Hills in the United States of America; Staro-Groznenskoe in the Russian Federation) and gas fields (Lacq in France; Caviaga in Italy; Gazli in Uzbekistan). Human-induced earth tremors occasioned by the exploitation of the gas-condensate deposits in Astrakhan can be predicted with a high degree of probability, given the geological structure of the rock containing the reservoir and the likelihood that it contains fracture failures.

10. It is clear from the foregoing how important it is to analyse and forecast possible developments in the geomechanical processes of rock and land-surface displacement and deformation during the exploitation of wells and the operation of underground storage facilities, from the point of view both of ensuring an appropriate degree of industrial and environmental safety and of reducing financial outlays on emergency and rehabilitative operations of various kinds to cope with the undesirable effects of geomechanical processes on industrial plant and on operations themselves.

11. In keeping with the requirements of Russian legislation and the regulations passed by the mining supervisory authorities on preservation of mineral resources and maintenance of industrial safety at hydrocarbon extraction facilities, mine-working operations must be accompanied by a system of mine-surveying and geodesic measurements of deformations of the land surface - so-called “geodynamic test sites”. Given the substantial size of mining tracts, the cost of monitoring stations and the significant unevenness in the deformation of the land within

the displacement trough that forms at the surface, the only sensible way of designing and setting up a monitoring system is on the basis of an analysis and forecast of geomechanical processes. Besides, the results of the measurements can only be interpreted (and unless one does this there is no point in setting up a monitoring system) in the light of the corresponding geomechanical calculations. It should be noted that mining tracts and areas to be used for underground storage facilities, including pipelines, compressor stations and so forth, are allowed to be developed if there is appropriate geological justification, including an analysis and forecast of displacements and deformations of the land surface, to hand.

12. Yet another category of geomechanical tasks arises when underground storage facilities in rock salt for gaseous and liquid hydrocarbons are constructed, operated, maintained and dismantled. The first such task is to ensure the stability and tightness of the workings for the specified operating period; this involves, first, determining the long-term stability of the geometrical form and size of the workings under various geological conditions, and setting safe technological operating parameters for underground reservoirs (maximum and minimum back-pressure in the product being stored, and regimes for withdrawal and injection). Despite the undeniable accomplishments of Soviet, Russian and foreign scientists in tackling various aspects of this task, it cannot yet be regarded as definitively resolved.

13. Building and operating underground storage facilities in rock salt also involves ensuring the stability and tightness of the operating bores in the underground reservoirs and analysing and forecasting the displacement and deformation of the overlying rock mass and the ground surface. In this case, however, these tasks have special characteristics due, in the main, to the rheological properties of rock salt and the specifics of building and operating underground storage facilities in rock formations.

14. Specific geomechanical tasks arise when underground reservoirs constructed by means of nuclear explosions in rock-salt deposits need to be maintained or dismantled, principally owing to the technology used to construct the reservoirs, i.e. the dynamic effects on the surrounding rock mass of super-high pressures and temperatures which cannot be reproduced in the laboratory but fundamentally alter the properties and state of the rock in the shocked region. The only way to analyse the geomechanical processes of deformation and destruction of the surrounding rock, to be able to forecast the formation in the rock mass of potential channels through which radionuclides can migrate from the underground caverns into the rock mass and into aquifers, is to solve the inverse geomechanical problems in which the initial properties and state of the rock mass are re-established by means of full-scale measurement of the results of the processes (e.g. well-head pressures, residual volumes of underground caverns).

15. Nowadays underground gas and oil storage facilities in rock-salt deposits are planned using geomechanically justified design solutions for the reservoirs and their basic technological operating parameters. The geomechanical justification is grounded in detailed study of the mechanical and rheological properties of the rock salt where the facility is to be constructed, and a field laboratory with up-to-date experimental equipment is set up for the purpose.

16. In contrast to underground gas and petroleum storage in rock salt, Russia makes virtually no use of geomechanical justification for the planning and technical decisions associated with the exploitation of hydrocarbon deposits and the underground storage of gas in porous structures if one leaves aside the mine-surveying systems set up at a few fields and storage facilities, and as a

rule no attempt is made to interpret the measurements of land deformation those systems produce. The reason for this situation is the evident absence of any proper study of the geomechanical processes accompanying the development of oil and gas deposits and the operation of underground gas storage facilities in porous structures, and the resulting lack of the necessary means and methods to analyse, monitor and forecast those processes. Formulating such means and methods may be regarded as one of a series of pressing technical problems within the industry.

17. If the tasks mentioned above are to be successfully tackled it is essential, in our view, to set up geomechanical monitoring systems at oil and gas fields and storage facilities that are under construction or in operation. The main purposes of doing so would be to assess the characteristics and state of the surrounding and overlying rock masses, and how they change over distance and time; to develop geomechanical models of working fields and storage facilities; to refine the geomechanical models by performing a range of measurements of the manifestations of geomechanical processes, including mine-surveying measurements of land surface deformations, then comparing the measurement data with the forecast values for the nature and intensity of the geomechanical processes; to forecast displacement, deformation and collapse in the surrounding and overlying rock masses using forecast and actual technical parameters for the development of oil and gas fields and the operation of underground storage facilities; and to assess the effects of geomechanical processes on underground and above-ground engineering structures and plant, justify action to protect them, and ensure that they are environmentally and industrially safe.

18. Besides setting up geomechanical monitoring systems, we consider it advisable to create a Russian databank on manifestations of geomechanical processes during the development of oil and gas fields and the operation of underground storage facilities - their nature and intensity, and the extent to which they affect underground and above-ground structures and plant. The bank would also contain the results of mine-surveying measurements of land surface deformations, data on accidents at working wells, anomalous surges in seam pressure with reference to the technological parameters of well or storage facility operation and so forth. Creating such a databank will make it possible to produce a geomechanical typology of the conditions under which gas and gas-condensate deposits are worked and storage facilities are operated, and will substantially ease the development of means and methods of analysing, forecasting and monitoring the development of geomechanical processes.
