Substantiation of convergent technology data for the Ilets rock salt mining

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Abstract. Using the applied theory of honeycomb structures, the authors propose and evaluate mining system alternates based on the structure of honeycombs for a rock salt deposit. The new-developed nature-like convergent geotechnology enables the loss of the useful mineral to be reduced from 40–60% to 15% at the preserved geodynamic safety of mining. The scope of the discussion embraces the variants of ore extraction from vertical stopes bottom-up using assemblies of mechanized equipment and top-down with a mechanical device reaming a pilot hole for useful mineral to be by-passed to an accumulation horizon.

1. Introduction

The upper explored portion of the Ilets deposit dome down to a depth of 700 m is composed of a salt wall with areal size of 2×1 km. The deposit represents a salt dome enclosed in by loose sandy pebble formation from above. The geophysical survey proves the salt dome down to a depth of 1000–1200 m and below. At a depth of 1600 m the dome size is 6×4 km. The salt structure thickness exceeds 2.6 km. This unique salt needs no beneficiation. The processing only consists of crushing and sizing.

The 200 years-long operation of the Ilets rock salt deposit was unordered. There were both open and underground mines (Elizavetinskaya, Mariinskaya). The latter lasted not long and were flooded. The flooding of those mines, as well as of Mine 1, was explained by their construction in the top jointed and karst portion of the salt wall.

Currently Mine 2 is developed using the room-and-pillar systems with rib pillars left under waterproof strata 130 m thick of Mine 1. Earlier salt mining on level (-132)–(-160) m of Mine 2 used drilling-and-blasting, at the present time, on level (-185)–(-215) m, shearer mining is used.

Safe and efficient mining in the presence of the flooded mine is ensured owing to: flooding protection of Mine 2, prevention of water encroachment in underground openings, maintenance of integrity of objects on the ground surface and by avoidance of high loss of rock salt [1–3].

According to the new mining project for the Ilets rock salt deposit, production on level (-240)–(-270) m is meant for 15 years (2018–2032) at the capacity to 1700000 t/yr [4, 5].

The room-and-pillar mining system has justified parameters, involves rib pillars, crown pillars of sufficient dimension are left between production horizons, rib pillars on neighbor levels are arranged
coaxially, and the stopes mined-out in the last century with cut rib pillars prone to extensive strains these day are backfilled [6–10].

The modern level of the technological development in underground mining of solid minerals using the open stoping systems features high degree of mechanization of mining operations and their low labor input owing to wide application of drilling-and-blasting or shearing (Figure 1). A sure pay for such high efficiency is unsafety governed by personnel presence in the stoping area. The main thin also is high loss of proven reserves in rib pillars; the loss reaches 40–50% and grows to 60% as mining proceeds to deeper levels. This situation totally conflicts with modern standards of resource saving and sound nature management [11–14]. Thus, considering the dominant trend of continuous growth in mining depth in promising mineral fields and deposits, it is of the current concern to find cardinally new geotechnologies, including convergent geotechnologies, for safe and complete extraction of proven reserves based on alternative procedures and equipment.

![Figure 1. Scheme of stoping with rib pillars: RP—rib pillar; S—stope; H—mining depth $\sigma_1$—vertical stresses.](image)

2. Convergent nature-like geotechnology with honeycomb mine structure

The mining practice in Russia and in the world shows that geotechnologies have undergone no considerable changes. The underground mining methods are customary for decades, including methods of support (natural and artificial) as well as systems with caving of ore and enclosing rock mass.

A breakthrough of the latest two decades is the high-productive machinery, with effective control and communication on duty in open pit and underground mining of solid minerals [15]. The use of the new equipment induces structural modification of the conventional mining system. At the present day, we have that productivity of labor is greatly increased, production cost is cut down, production profitability is raised, intensity of mining operations is enhanced while efficiency of subsoil management is improved in terms of complete mineral extraction.

At the modern stage of geotechnological development, it is required to set new challenges in science and technology such as development of new convergent mining technologies based on blending of mining and non-mining sciences and techniques, for the first turn, information, communication, nature-like, cognitive and nano technologies. Furthermore, it is required to develop and introduce automated control of mining processes based on wide application of digital technologies.

It is known that the simplest way of finding an alternative to make an opposite decision as against the currently applied. The same approach was accepted in mining the Ilets rock salt deposit. New principles were formulated for the alternative convergent nature-like geotechnology which provided geomechanically validated minimization of loss of rock salt in pillars by 15% at the preserved geodynamic safety considering specific geological structure of the deposit.

The criticality of the new geotechnology consists in the idea to turn the stoping front advance by 90°, which means transition from horizontal stoping to upward or downward breaking with drillog-
out or VCR. This cardinaly changes structure, behavior and geometry of the man-altered subsoil, both in the zone of total destruction and in the geophysical ecotone [12–14].

The geometry of man-altered subsurface allows searching ideas in biological systems. In natural biological systems, there are many structures that ensure high strength and stability at minimal quantity and mass of material. For instance, structures represented by external shells with internal volume filled with numerous fine brattices arranged spatially depending on directions of external loads. Such structure is typical of culms or bones of mammals, which take up vertical loads when in motion. In the modern bionics, these structural solutions of the nature are reproduced in the form of aircraft engineering, shipbuilding and some other industries.

Regarding the problem when the change in the stoping front advance direction cardinaly varies the geomechanical behavior of undermined and overmined rock mass, it is required to find an adequate physical model of such geotechnical system. Considering evident structural analogy between this system and honeycomb structures, it is expedient to assume the physical model of a three-layer load-bearing structure with honeycomb interior (Figure 2). A signature of such structures is the fact that their stability relative to compressive loading is achieved not due to the increased quantity of substance in the load-bearing structure as in the room-and-pillar mining systems but owing to high relative stiffness of the interior due to geometry of cells characterized by such parameters as size of a face (or diameter of escribed circle) and thickness of wall.

![Figure 2. Three-layer load-bearing honeycomb structure: 1—top layer; 2—honeycomb interior; 3—bottom layer.](image)

The review of the special literature [16] shows that depending on the level of loading, saving in weight in case of honeycomb structures can reach 30% and more as against the opening-and-support structure. This figure means that the modified geotechnology may reduce the mineral loss in pillars by a third without altering geodynamic stability of the geotechnical system. The methods to calculate parameters of cellular structures in the other industries are well developed. For example, the calculation procedure can use the IPKON methodology of homeostatic transformation applied to creating a general concept of convergent nature-like geotechnologies for underground ore mining.

On the whole, efficiency of a geotechnology is governed by feasibility of synchronizing stoping operation owing to their separation by geometry, while quality of stoping is ensured by desynchronization of ore and gangue discharge from a definite block of ore and rock mass.

This trend of quality change in the geotechnology coincides with the forecasted advancement of promising energy- and resource-saving technologies in the line of overlapping of processes based on the use of equipment with new methods of rock fracture.

The application range of such geotechnology embraces basic geological types of mineral salt deposits, as well as steeply dipping ore and coal bodies of high thickness, including diamond pipes.

The key process within this geotechnochnology is creation of vertical openings (combs) of circular section with diameter from 1 to 6 m in rock mass by drilling-out with drilling facilities.

Drilling facilities of the required performance for underground mining are currently not manufactured in Russia [17]. The first application of the developed convergent technology is planned in the deposits of mineral salts, kimberlite, coal and ore with hardness to 5–7 on Protodyakonov’s
scale. To this effect, it seems to be advisable to use a model series of domestic drill rigs represented by three self-propelling and three portable models. Also, it is recommended to use machines of foreign manufacture, for example, Robbins tunnel boring machines.

As an alternative to foreign reamer bits for vertical circular cross-section openings, the Institute of Mining, SB RAS proposes a new impact power technology and equipment with rotary hammering tool [18–21]. Such engineering solution localizes damaged rock zone as compared with blasting. Moreover, the rotary hammer eliminates generation of coarse fragment to be preliminary crushed before processing. This approach, by pre-estimates, may reduce energy input of drilling as a key process by several times as compared with blasting and disintegration methods.

3. Application of cellular structure theory

It is found that the change in the stoping front advance direction cardinally varies the geomechanical behavior of the undermined and over mined rock mass. In view of the evident structural analogy between this system and honeycomb structure, it is expedient to model this system as a three-layer load-bearing structure with honeycomb interior (Figure 3).

![Figure 3. Development of extraction panel by convergent nature-like geotechnology with coaxially arranged stopes in the Ilets deposit: 1—circular cross-section stopes; 2—drilling rig; 3—pilot holes; 4—accumulation horizon; 5—drilling and ventilation horizon; 6—circumferential panel drift.](image)

The three-layer structure possesses many advantages, including high stability of bearing layers and considerable bending stiffness [16]. Furthermore, they have high quality form and surfaces; high functional reliability because of the absence of stress raisers; high produceability and possibility of efficient cutting of vertical stopes by high-duty boring machines.

When constructing optimal-designed panels under compression, the stress state governed by the ratio of the destructive force to the total cross-section area of the panel is given by:

\[ \vec{N} = \frac{N}{EF^2}, \]

where \( N \) is the load applied to the panel; \( E \) —is the elasticity modulus of rocks; \( l \) is the length of the panel in the line of compression.

It is known that in any cross-section of a pillar or a bent beam, the normal stresses obey the linear distribution law with maximal values in the external layers and zero value in the middle layer. Thus,
only peripheral parts of a geomaterial in the pillar cross-section work, the geomaterial closer to the middle layer weaker participates in the work. Placement of major portion of geomaterial in external pillars to ensure stiffness under bending moment makes the external layer to undergo lateral forces and provides efficient joint work of the external layers. The middle layer in this case can possess relatively low stiffness. On the whole, the strength and stability of the three-layer structure is influenced by a set of parameters characterizing physical and mechanical properties of rock composing the three-layer mine structure.

Figure 4 shows a possible variant of a cellular design. Structurally, the cellular form is anisotropic: stiffness and shear strength of pillars across and along the strike differ. Another factor of anisotropy is strength and compressive (tensile) stiffness in perpendicular direction to the pillar surface. Geomaterial of pillars is described by the bulk weight, elasticity modulus $E_z$, shear moduli $G_{xz}$, $G_{yz}$ and strength characteristics $\sigma_z$, $\tau_{xz}$, $\tau_{yz}$. These characteristics can be determined in lab tests of physical and mechanical properties of rocks. The common parameters to describe the cellular geometry are the the round stope diameter $d_{\text{stopes}}$, stope width $b$, stope height $h$ and wall thickness $\delta_{\text{stopes}}$. In case a cell has an imperfect round shape, its diameter is determined as the diameter of the inscribed circle.

Figure 4. Analytical model of three-dimensional structure of pillars in convergent nature-like geotechnology with parallel arrangement of stopes: Z, X, Y—coordinate axes; $\sigma_z$, $\sigma_x$, $\sigma_y$—principal normal stresses, MPa; $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$—shear stresses, MPa.

Geomaterial is the weakest point in the cellular structure. For this reason, it is the prime task to find allowable stresses. Furthermore, it is required to know moduli of elasticity and shear of the cellular structure elements. For instance, neglect of real shear stiffness yields the calculation error by 2–2.5 times, while the error of strains can be 2–3 times.

The other difficulties in reliable calculation of allowable stresses and elasticity moduli of cellular structure elements are presented by rock mass discontinuities given rocks have different moduli.

The calculated dependences may only be used in parametric studies and pre-design to find an approximate initial variant. The final conclusion on the values of the allowable stresses and elasticity moduli depending on safety factor of a cellular structure will be made based on the full-scale tests in the Ilets deposit (physical simulation, numerical modeling and pilot tests).
In a general case, a cellular structure can be assumed as an anisotropic body, nonuniform in volume, with physical and mechanical characteristics represented by (Figure 4): elasticity modulus $E_z$; shear moduli $G_{xz}$, $G_{yz}$; allowable stresses $[-\sigma_z]$, $[-\tau_{xz}]$, $[-\tau_{yz}]$.

The cellular structure ensures effective joint work of the whole system of rib pillars. For a cell of a certain height and width, the volume is calculated together with the volume of stope in the cell, bulk volume of pillar in the cell, subsidence of the cell under loading, shear modulus of rock composing the cell pillar under strains due to action of shear stresses, shear angles of the cell faces under the action of shear stresses, etc.

The cell should be considered in its joint deformation with load-bearing layers. As a result of interaction between the load-bearing layers and the cell, additional self-balancing forces appear and lead to redistribution of shear angles of the cell forces and to bending of the load-bearing layers. The calculations should also estimate approximate influence of the bending stiffness of the load-bearing layer on the shear modulus $G_{xz}$ of rock composing pillars.

In the conditions of maximal loading, the cellular structure elements lose load-bearing capacity. For this reason, at the design stage of the proposed convergent geotechnology, the physical and mechanical properties of rocks should be qualitatively determined. First, the load-bearing capacity is lost by the cell faces (pillars); then, total disintegration of the cellular structure takes place.

Solution of problems on destructive loads encounters sequences of equilibrium states. Moreover, the calculation is complicated due to required to account for unavoidable deviations from the right geometrical form, which have a strong influence on the values of the destructive loads as tests show. Reliable data can only be obtained from systematic testing; approximate estimates are only permitted at the preliminary design stage.

![Image](image_url)

**Figure 5.** (a) Vertical computational grids for Mine 2 and (b) safety factors of rib pillars in vertical; computational grid for all levels under mining (in Map3D [22]).
4. Mining variants with convergent geotechnology with cellular structures for the Ilets rock salt deposit

In 2017–2018 stress–strain analysis was performed for Mine 2 [5] on level (+118)–(-270) m, including the design level (-240)–(-270) m in Map3D environment [22], and stoping sequence was determined. It is found that the minimum safety factor of rib pillars after total joint extraction of salt reserves was 2.0 on level (-132)–(-160) m; 1.9 on level (-185)–(-215) m; 1.7 on level (-240)–(-270) m (Figure 5). The allowable safety factor for pillars, subject to high reliability of input parameters, is assumed as ≥1. The numerical modeling data mean that the rib pillars keep stable during mining on level (-240)–(-270) m and the selected sequence of stoping can be assumed justified. Induced jointing in the crown pillar 130 m thick above level (-132)–(-160) m propagates not deeper than to 25 m in rock mass at insignificant intensity; thus, no instability is anticipated in roof of the stopes. Mine 2 is going to be developed according to the project for 15 years [4].

For mining under level –270 m of the Ilets deposit, the convergent technology with cellular structure provides construction of new Mine 3 under the water-proof strata of Mine 2, with possibility of flooding in the future. Salt reserves of Mine 3 are accessed by two shafts independently of Mine 2, these two mines are spaced.

Considering project capacity of the new mine to 3 Mt/yr, it is planned to extract reserves from level 1 with height of 80–100 m during 35 years. There are structural variants of mining: 1—bottom-up stoping with Robbins boring machines from Atlas Copco or Rhino boring machines from Sandvik (Figure 6); 2—top-downward stoping using drilling facility with reaming out of a pilot hole for passing rock salt; such device is being developed by the Institute of Mining, SB RAS (Figure 7). In these variants, development openings have cross-section from 16 to 36 m²; the stopes have height of 68–88 m (72–92 m) and diameter of 3–6 m; the normal distance between the vertical stopes is 2 m; the distance between the stope axes is 8–14 m; the rate of stoping is 5–6 days per one vertical stope; production needs simultaneous operation of 4–5 drilling machines.

At the present time, the field research implemented in the Ullets deposit involves construction of various structure physical models of the future Mine 3; these models are placed directly in the mine and allow monitoring of deformation processes; the numerical model is also designed in Map3D [22]. In the nearest future is planned to accomplish feasibility study of the access variants, structural designs of the convergent nature-like geotechnology as well as ecological package of preservation of natural ecosystems [23, 24].

5. Conclusions

The aim the research into convergent geotechnologies is to interconnect the occurrence conditions of minerals and convergent approaches to their extraction, to preserve subsoil for subsequent use and to determine behavior of the convergent geotechnologies and processes in the dynamics of mining.

This paper has voiced the major task of the research implemented these days in the Ilets rock salt deposit as to create a scientific framework for eco-friendly, convergent nature-like mining technology with three-layer honeycomb structures and the relevant mining methods. The scope of this research embraces such areas of modern mining as functioning of physicotechnical and geotechnical processes, similarity technologies, and formation of design principles and application methods for convergent technologies for rock salt deposits, steeply dipping and thick ore bodies and coal seams, as well as diamond pipes, etc.

Creation of new alternative convergent geotechnologies aimed to ensure geomechanically justified minimization of mineral losses at the preserved geodynamic safety, with regard to geological structure of mineral deposits, as well as the through application of nature-like geotechnologies is a priority area of research implemented at the Center for Applied Geomechanics and Convergent Mining Technologies established at the College of Mining of the National University for Science and Technology–MISIS in 2017.
Figure 6. Mining in with cellular structure mine with stoping bottom-upward using drilling facilities: $H_\text{min}$—height of level; $B$—width of horizontal openings; $H$—height of horizontal openings; $d_u$—diameter of stopes; $d_u$—height of crown pillar.
Figure 7. Mining in with cellular structure mine with stoping top-downward using drilling facilities with reaming of pilot holes for mineral passing to accumulation horizon.

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