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Analysis and preparation of initial data for building a geological and geomechanical model of the area at the Verkhnekamskoye potassium-magnesium salt deposit

Olesya O. Lebedeva

Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)

Анализ и подготовка исходных данных для построения геолого-геомеханической модели участка Верхнекамского месторождения калийно-магниевых солей

О.О. Лебедева

Пермский национальный исследовательский политехнический университет (Россия, 614990, г. Пермь, ул. Комсомольский проспект, д. 29)

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Many years of experience in the development of potash deposits, in particular the Verkhnekamennoye potassium-magnesium salt deposit, has shown that the most unfavorable and detrimental consequence is the flooding of the entire mine field or its section. As a rule, the cause of flooding is the formation and development of technogenic water-conducting cracks or the development of existing cracks in the massif, which are most often associated with zones with weakened physical and mechanical properties. The most detailed distribution of properties can be obtained by creating a geological and geomechanical model. To create such a model, it is necessary to analyze the existing factors that affect the state of the rock mass and workings, as well as identify and prepare the necessary initial data. The main influencing factors include the geological features of the structure of the Solikamsk depression, various technogenic events that have manifested themselves in connection with the development of the industrial reserves of the deposit, the physical and mechanical properties of host rocks and productive strata, as well as the development of mining operations and their current situation. The experience of geomechanical analysis of man-made accidents that have occurred on the territory of the Verkhnekamennoye potassium-magnesium salt deposit showed that the most powerful influencing factor was the physical and mechanical properties of the rocks of the water-protective strata. To obtain a reliable distribution of these parameters in the massif and in productive layers, usually try, first of all, by combining geophysical and geomechanical methods. Within the framework of this article, it was proposed to integrate geological, geophysical and geomechanical approaches when creating a geological and geomechanical model of a water-protective stratum section. As initial data, the geological description of well cores, geophysical surveys in wells, physical and mechanical properties of rocks were used. The processing of available data on wells allowed creating a three-dimensional model of the distribution of the longitudinal wave velocity, in turn, the statistical dependences for the two main parameters of physical and mechanical properties (modulus of elasticity and compressive strength) on the velocity of the longitudinal wave make it possible to obtain the values of these properties at any point in the model , on the basis of which the simulation of the stress-strain state and the forecast of the state of the rock mass and workings are further carried out.

Ключевые слова:
междушахтный целик, геофизические исследование скважин, скорость продольной волны, модуль упругости, предел прочности на сжатие, геолого-геомеханическая модель, водозащитная толща, Верхнекамское месторождение калийно-магниевых солей.

Многолетний опыт разработки калийных месторождений, в частности Верхнекамского месторождения калийно-магниевых солей (ВКМКС), показал, что самым неблагоприятным и пагубным последствием является затопление всего шахтного поля или его участка. Как правило, причиной затоплений является формирование и развитие техногенных водопроводящих трещин или развитие существующих трещин в массиве, которые чаще всего приурочены к зонам с ослабленными физико-механическими свойствами. Наиболее подробное распределение свойств можно получить, построив геолого-геомеханическую модель. Для создания такой модели необходимо проанализировать существующие факторы, влияющие на состояние массива горных пород и выработок, а также обозначить и подготовить необходимые исходные данные. К основным влияющим факторам следует отнести геологические особенности строения Соликамской впадины, различные техногенные события, которые проявили себя в связи с отработкой промышленных запасов месторождения, физико-механические свойства вмещающих пород и продуктивных пластов, а также развитие горных работ и их текущее положение. Опыт геомеханического анализа произошедших техногенных аварий на территории ВКМКС показывает, что наиболее сильным влияющим фактором являются физико-механические свойства пород водозащитной толщи. Получить надежное распределение данных параметров в массиве и в продуктивных пластах пытаются, прежде всего, комбинированием геофизических и геомеханических методов. В рамках данной статьи предлагается комплексирование геологических, геофизических и геомеханических подходов при создании геолого-геомеханической модели участка водозащитной толщи. В качестве исходных данных используется геологическое описание колонок скважин, геофизические исследования в скважинах, физико-механические свойства пород. Обработка имеющихся данных по скважинам позволяет создать трехмерную модель распределения скорости продольной волны, в свою очередь, статистические зависимости для двух основных параметров физико-механических свойств (модуль упругости и предел прочности на сжатие) от скорости продольной волны позволяют получить значения данных свойств в любой точке модели, на основе которой в дальнейшем производится моделирование напряженно-деформированного состояния и прогноз состояния массива горных пород и выработок.

© **Olesya O. Lebedeva** (Author ID in Scopus: 57217631759) – Junior Researcher at the Department of Surveying, Geodesy and Geoinformation Systems (tel.: +007 (982) 245 67 86, e-mail: lesli.lebedeva@gmail.com).

© **Лебедева Олеся Олеговна** (ID Scopus: 57217631759) – младший научный сотрудник кафедры маркшейдерского дела, геодезии и геоинформационных систем (тел.: +007 (982) 245 67 86, e-mail: lesli.lebedeva@gmail.com).

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Introduction

The distribution of rocks physical and mechanical properties in the water-protective strata (WPS) at the Verkhnekamskoye potassium-magnesium salt deposit (VPMSD) is the most uncertain parameter while solving numerical modeling problems of the stress-strain state of the WPS for various parameters of the development system. Currently, there are numerous attempts to obtain a picture of the distributing geomechanical characteristics using geophysical methods [1–6]. However, these methods do not allow establishing a quantitative relationship between the obtained geophysical parameters and the geomechanical characteristics of the WPS rock mass. And the direct use of rocks elastic-strength characteristics also does not allow even an approximate solution to the problem of constructing the distribution of these characteristics in the massif, since in this case the researcher operates with point values [7–10]. This article presents the construction of a geological and geomechanical model of the WPS section in the area of the inter-mine pillars SPMD-1 – SPMD-2 – SPMD-3 (Fig. 1) based on the integration of geophysical data obtained during drilling of salt exploration wells and geomechanical data obtained during testing of the physical and mechanical properties of salt rock samples.

Initial data required for constructing a geological and geomechanical model

The main idea of constructing a geological and geomechanical model of any deposit section aimed at subsequent geomechanical modeling the stress-strain state of the analyzed section during the development of its reserves is to obtain a real distribution of geomechanical characteristics in the rocks of the WPS and productive formations [11–14]. It should be noted that such an approach has long been used in the development of hydrocarbon deposits and only recently has it begun to be applied in the development of solid mineral deposits [15–25]. In this regard, the initial data required to construct the model included a geological description of well columns, geophysical studies in wells (GSW) including oil wells drilled in the VPMSD territory, and correlation dependencies between the physical and mechanical properties of the rocks that make up the massif and distributed geophysical parameters, primarily wave velocity.

Geological description of well columns. The sample consists of 33 wells. Each well was analyzed separately. Processing of geological description data showed that not all wells were drilled to the marker clay, many of them only penetrated the transitional layer, and therefore cannot be used to build a geological and geomechanical model.

GSW data. The things which are of greatest interest appear to be acoustic logging (AL), gamma logging (GL), and neutron gamma logging (NGL). Only 23 of considered wells has GSW data. GL was mainly carried out to the entire depth of the wells. It is worth noting that only two wells have AL data - No. 234c and 1036. Using well No. 234c as an example, it can be seen that the studies were carried out in a fairly limited interval (within a depth of 150-175 m). Figure 2 shows an example of the distributing the longitudinal wave velocity in the well – V_p, the corresponding strength distribution in the studied interval obtained on the basis of the dependence – UCS, as well as the strength distribution along the wellbore, downloaded from the model – UCS_3D.

Properties of the rocks that make up the massif. The most common parameter from the physical and mechanical properties of the rocks that make up the massif is the strength of the rock which is determined based on the results of rock testing for uniaxial or triaxial compression by specialists of the MI UB RAS. As a rule, rocks are tested under uniaxial conditions. As part of the creating the geological and geomechanical model, special tests were carried out on the PIK-UIDK/PL unit (PNRPU) to determine the relationship between the geomechanical characteristics of salt rocks and the geophysical characteristics of the geological section, in particular with the velocity of longitudinal and transverse waves. The obtained dependencies used in creating the geological and geomechanical model [15–33] will be shown below.

Constructing geological and geomechanical model

The geological and geomechanical model was constructed in the IRAP RMS program. The final geological model contains 10 million cells; the division method is proportional. The average element size is 0.25 m vertically and 50 m horizontally.

With the use of information connected with salt and oil wells, it became possible to construct a three-dimensional model of the distributing the main parameter - the longitudinal wave velocity V_p in the area of the SPMD-1 – SPMD-2 – SPMD-3 pillars.

The AKL data were available only in limited intervals, in connection with which the AL was interpolated to the entire cube of the three-dimensional model. Figure 3 shows an example of interwell correlation of horizons in the geological model.

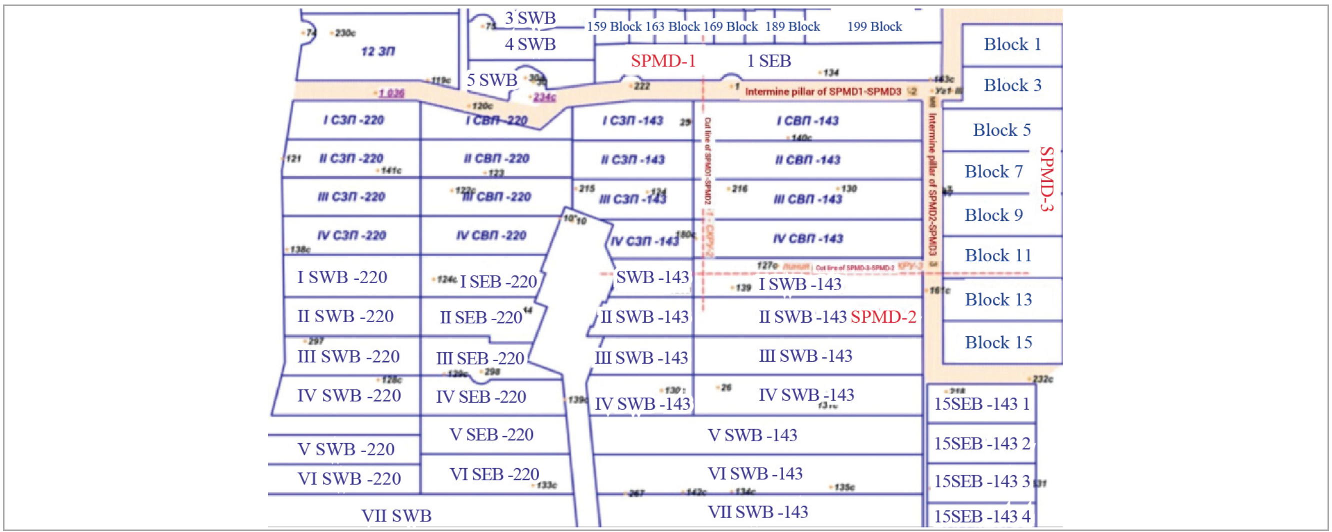

Fig. 1. Location of mine fields

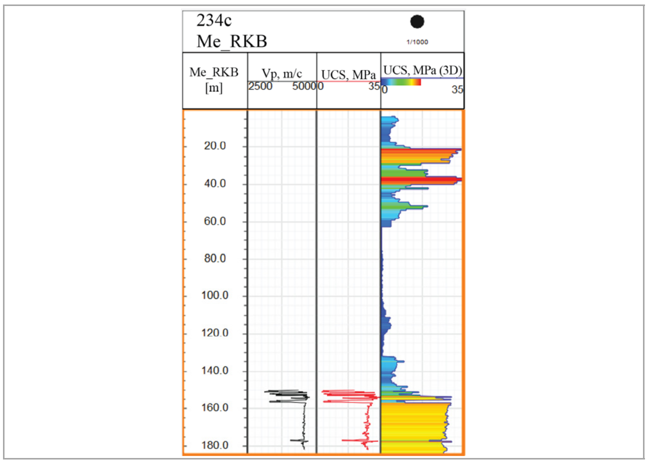

Fig. 2. Example of interpretating acoustic logging data and the obtained distribution of strength along the wellbore

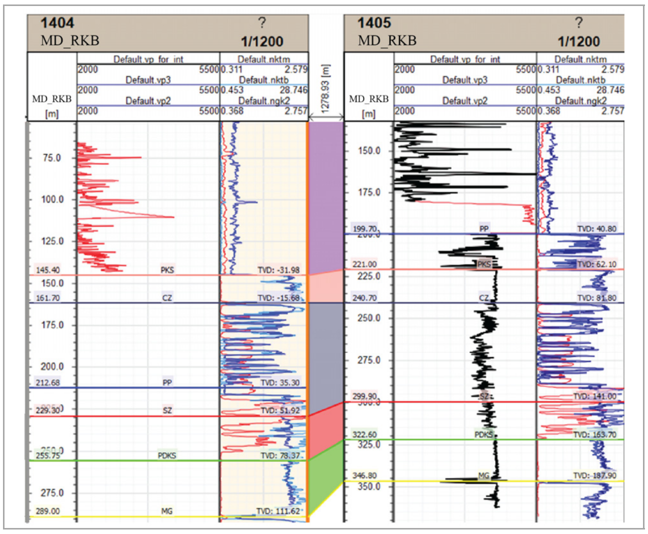

Fig. 3. Example of interwell correlation of horizons in a geological model

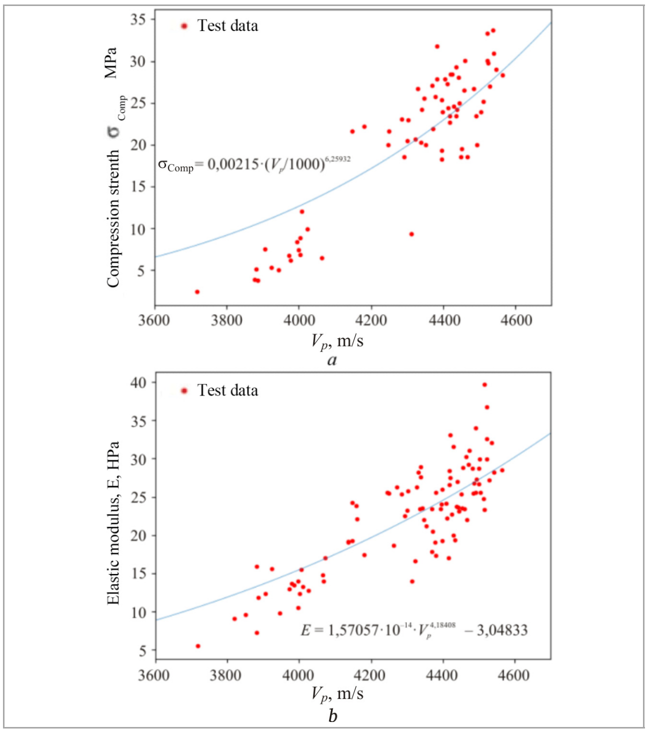

Fig. 4. Results of PNRPU tests: *a* – dependence of the compressive strength on the longitudinal wave velocity according to [11–14, 17]; *b* – dependence of the elastic modulus on the longitudinal wave velocity

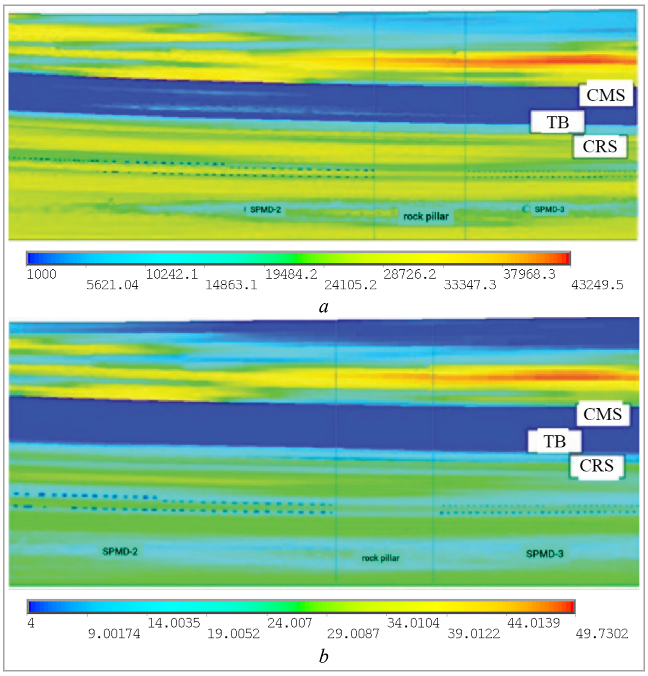

Fig. 5. The area of the inter-mine pillar SPMD-2 – SPMD-3: *a* – distribution of the elastic modulus along the calculated section; *b* – distribution of the compressive strength limit along the calculated section

The parameter was distributed using geostatistical methods, in particular the Kraiging method in combination with the conditional modeling method to recreate the natural variability of the modeled parameter. The parameters were selected based on variogram analysis after data normalization.

The created model allows one to obtain the distribution of elastic and strength properties based on statistical dependencies between the longitudinal wave velocity and such parameters as the elastic modulus and the compressive strength limit (Fig. 4).

As a result, geomechanical sections of the elastic modulus distribution (Fig. 5, *a*) and the compressive strength limit (Fig. 5, *b*) were constructed along the characteristic profile lines in the area of inter-mine pillars. In the future, geomechanical modeling stress-strain state (SSS) of the WPS rock massif and the pillars themselves will be performed based on these sections. As an example, a section along the pillar between the mine fields SPMD-2 – SPMD-3 is given.

Conclusion

Analysing and forecasting the state of a rock massif is impossible without a high-quality geological and geomechanical model. To build such a model, preliminary analysis and preparation of initial data are required, since taking into account the influencing factors and including the necessary information in the model subsequently determine the result of modeling as a whole and, accordingly, the subsequent forecast.

The geological description of well columns, geophysical studies in wells, and physical and mechanical properties of rocks were used as initial data necessary for building the model.

Based on the initial data, a three-dimensional model of the distributing the longitudinal wave velocity in the area of the interested pillars SPMD-1 – SPMD-2 – SPMD-3 was built.

Based on the statistical dependencies between two main indicators of physical and mechanical properties - the elastic modulus and the strength limits - on the longitudinal wave velocity, the distributions of these properties for the constructed model were obtained. Characteristic sections were selected along which the modeling the SSS of the rock massif of WPS and the pillars themselves will be performed in the future.

References

1. Sanfirov I.A., Babkin A.I., Priima G.Iu., Iaroslavtsev A.G., Prigara A.M., Fat'kin K.B. Seismorazvedochnye issledovaniia vodozashchitnoi tolshchi Verkhnekamskogo mestorozhdeniia kaliinykh solei [Seismic exploration of the water-protective strata of the Verkhnekamskoye potassium salt deposit]. *Gornyi zhurnal*, 2008, no. 10, pp. 45p48.
2. Sanfirov I.A., Stepanov Iu.I., Fat'kin K.B., Gerasimova I.Iu., Nikiforova A.I. Maloglubinnye geofizicheskie issledovaniia na Verkhnekamskom mestorozhdenii kaliinykh solei [Shallow geophysical surveys at the Verkhnekamskoye potash deposit]. *Fiziko-tekhnicheskie problemy razrabotki poleznykh iskopaemykh*, 2013, no. 6, pp. 71-77.
3. Sanfirov I.A., Babkin A.I., Baybakova T.V. Seismic CDP profiling in wells. *13^{TH} conference and exhibition on engineering geophysics. Engineering Geophysics*, 2017. Volume 2017, pp.1-10. DOI: 10.3997/2214-4609.201700420
4. Nikiforova A.I., Sanfirov I.A., Nezdanov V.M., Bogdanov R.A. Integrated Interpretation of Ground-Based and Mine Seismic Surveys in the Potash Deposit Areas with a Complicated Geological Structure. *Conference Proceedings, Engineering and Mining Geophysics 2021*, 2021, vol. 2021, pp. 1-7. DOI: 10.3997/2214-4609.202152109
5. Tsarev R.I. Obosnovanie vybora modeli geologicheskoi sredy pri reshenii priamoi zadachi seismorazvedki MOV OGT na VKMS [The rationale for selecting the geological environment model in the seismic CDP survey forward solution on the Verkhnekamskoye salt deposit]. *Geofizika*, 2018, no. 5, pp. 18-23.
6. Zhukov A.A., Prigara A.M., Tsarev R.I., Shustkina I.Iu. Sposob shakhtnoi seismorazvedki dlia izucheniia osobennostei geologicheskogo stroeniia VKMS [Method of mine seismic survey for studying geological structure features of Verkhnekamskoye salt deposit]. *GIAB*, 2019, no. 4, pp. 121-136. DOI: 10.25018/0236-1493-2019-04-0-121-136
7. Ukazaniia po zashchite rudnikov ot zatopleniia i okhrane podrabatyvaemykh ob"ektov na Verkhnekamskom mestorozhdenii kaliino-magnievykh solei [Guidelines for the protection of mines from flooding and the protection of undermined facilities at the Verkhnekamskoye potassium-magnesium salt deposit]. Saint Petersburg, Perm': GI UrO RAN, 2014, 130 p.
8. Metodicheskie rekomendatsii k “Ukazaniiam po zashchite rudnikov ot zatopleniia i okhrane podrabatyvaemykh ob"ektov na Verkhnekamskom mestorozhdenii kaliino-magnievykh solei” [Guidelines for the “Guidelines for the protection of mines from flooding and the protection of undermined facilities at the Verkhnekamskoye potassium-magnesium salt deposit”]. Saint Petersburg, Perm': GI UrO RAN, 2014, 66 p.
9. Bariakh A.A., Asanov V.A., Pan'kov I.L. Fiziko-mekhanicheskie svoistva solianykh porod Verkhnekamskogo kaliinogo mestorozhdeniia [Physical and mechanical properties of salt rocks of the Verkhnekamskoye potassium deposit]. Perm': Permskii gosudarstvennyi tekhnicheskii universitet, 2008, 199 p.
10. Bariakh A.A., Konstantinova S.A., Asanov V.A. Deformirovanie solianykh porod *[*Deformation of salt rocks]. Sverdlovsk: UrO RAN, 1996,180 p.
11. Kashnikov Yu., Ermashov A., Shustov D., Khvostantcev D. The increasing of exploitation safety of potassium salt deposit based on geological-geomechanical simulation. *EUROCK 2018: Geomechanics and Geodynamics of Rock Masses*, 2018, vol. 2, pp. 1425-1430.
12. Kashnikov Iu.A., Ermashov A.O., Efimov A.A. Geologo-geomekhanicheskaia model' uchastka Verkhnekamskogo kaliinogo mestorozhdeniia [Geological and Geomechanical Model of the Verkhnekamsk Potash Deposit Site]. *Zapiski Gornogo instituta*, 2019, vol. 237, pp. 259-267. DOI: 10.31897/pmi.2019.3.259
13. Kashnikov Iu.A., Ermashov A.O., Shustov D.V., Lebedeva O.O. Sozdanie geologo-geomekhanicheskoi modeli Verkhnekamskogo mestorozhdeniia kaliinykh solei [The creation of a geological and geomechanical model of the Verkhnekamskoye potassium salt deposit]. *Marksheiderskii vestnik*, 2019, no. 1 (128), pp. 39-45.
14. Kashnikov Yu.A., Shustov D.V., Ermashov A.O. Solving the problems of exploitation safety of potassium salt deposit based on joint application of geophysical and geomechanical studies. *EUROCK 2021: Mechanics and Rock Engineering, from Theory to Practice 20-25 September*. Turin, Italy, 2021. DOI: 10.1088/1755-1315/833/1/012084
15. Kashnikov Iu.A., Gladyshev S.V. et al. Geologo-geomekhanicheskaia model' Astrakhanskogo gazokondensatnogo mestorozhdeniia [Geological and geomechanical model of the Astrakhan gas condensate field]. *Gazovaia promyshlennost'*, 2012, no. 3, pp. 29-33.
16. Shustov D.V., Kashnikov Yu.A., Ashikhmin S.G., Kukhtinskiy A.E. 3D geological geomechanical reservoir modeling for the purposes of oil and gas field development optimization. *EUROCK 2018: Geomechanics And Geodynamics Of Rock Masses*, 2018, vol. 2, pp. 1425-1430.
17. Zoback M.D. Reservoir Geomechanics. Cambridge. University Press, 2007, 449 p.
18. Kashnikov Iu.A., Ashikhmin S.G. Mekhanika gornykh porod pri razrabotke mestorozhdenii uglevodorodnogo syr'ia [Rock mechanics in the development of hydrocarbon deposits]. Moscow: Gornaia kniga, 2019, 496 p.
19. Khatibi S., Ostadhassan M., Aghajanpour A., Kovaleva Yu., Mohammed R.A. Various effect of faults on mechanical earth models: A case study of integrated study. *Geomechanics and Geodynamics of Rock Masses*. Taylor & Francis Group. London, 2018, pp. 1395-1399.
20. Plumb R.A. Influence of composition and texture on the failure properties of clastic rocks. *SPE/ISRM 28022. In: Proc. Eurock ’94. Delft, Netherlands, 29-31 August 1994*, 1994, pp. 13-20. DOI: 10.2118/28022-MS
21. Chang C., Zoback M.D. et al. Empirical relations between rock strength and physical properties in sedimentary rocks. *Journal of Petroleum Science and Engineering*, 2006, vol. 51, pp. 223-237. DOI: 10.1016/j.petrol.2006.01.003
22. Sone H. Mechanical properties of shale gas reservoir rocks and its relation to the in-situ stress variation observed in shale gas reservoirs: Ph D. thesis, 2012.
23. Cuervo S., Adachi J., Lombardo E. Integration of 1D and 3D Mechanical Earth Models in oil shale plays. An example from the Vaca Muerta Formation (Argentina). *52nd U.S. Rock Mechanics/Geomechanics Symposium, ARMA*, 2018.
24. Shustov D.V., Kashnikov Iu.A. Razrabotka geologo-geomekhanicheskoi modeli uchastka Iurubcheno-Tokhomskogo mestorozhdeniia [Development of geological-geomechanical model of some part of Urubcheno-Tokhomskoe oil field]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2015, no. 4, pp. 26-31.
25. Kashnikov Iu.A., Shustov D.V., Kukhtinskii A.E., Kondrat'ev S.A. Geomekhanicheskie kharakteristiki terrigennykh produktivnykh ob"ektov neftianykh mestorozhdenii Zapadnogo Urala [Geomechanical properties of the terrigenous reservoirs in the oil fields of Western Ural]. *Neftianoe khoziaistvo*, 2017, no. 4, pp. 32-35. DOI: 10.24887/0028-2448-2017-4-32-35
26. Chertenkov M.V., Ruzin L.M. Predposylki dlia kompleksnogo ispol'zovaniia standartnogo karotazha i akusticheskikh issledovanii s tsel'iu prognoza koeffitsienta Puassona [Prerequisites to complex use of standard and acoustic logging for the forecast of a Poisson's ratio]. *Neftianoe khoziaistvo*, 2017, no. 1, pp. 16-18.
27. Barree R. A Composite Determination of Mechanical Rock Properties for Stimulation Design (What to do When You Don't Have a Sonic Log). SPE *108139 presented at the 2007 SPE Rocky Mountain Oil & Gas Technology Symposium*. Denver, Colorado, U.S.A, 2007. DOI: 10.2118/108139-MS
28. Eissa E.A., Kazi A. Relation between static and dynamic Young’s moduli of rocks. *Int. J. Rock Mech.*, 1988, vol. 25, pp. 479-482. DOI: 10.1016/0148-9062(88)90987-4
29. Fiaer E., Holt R.M., Horsrud P. et al. Petroleum Related Rock Mechanics. 2 ND Edition. Elsevier, 2008, pp. 391-434.
30. GOST 21153.2-84. Porody gornye. Metody opredeleniia predela prochnosti pri odnoosnom szhatii [GOST 21153.2-84. Rocks. Methods for determining the ultimate strength in uniaxial compression]. Moscow: Izdatel'stvo standartov, 1985, 10 p.
31. GOST 28985-91. Porody gornye. Metody opredeleniia deformatsionnykh kharakteristik pri odnoosnom szhatii [GOST 28985-91. Rocks. Methods for determining deformation characteristics under uniaxial compression]. Moscow: Izdatel'stvo standartov, 1991, 19 p.
32. GOST 21153.8-88. Porody gornye. Metody opredeleniia predela prochnosti pri ob"emnom szhatii [GOST 21153.8-88. Rocks. Methods for determining the compressive strength limit]. Moscow: Izdatel'stvo standartov, 1988, 10 p.
33. Wittke W. Rock Mechanics Based on an Anisotropic Jointed Rock Model. Ernst & Sohn Verlag, 2014, 876 p.
34. Ermashov A.O., Lebedeva O.O., Rysin A.I. The analysis of interbed stability with mathematical modeling methods. *Topical Issues of Rational Use of Natural Resources 2019*, 2020, vol. 1, pp. 173-182. DOI: 10.1201/9781003014577-22
35. Bariakh A.A. Kompleksnoe geofizicheskoe issledovanie potentsial'no-opasnykh uchastkov VZT na podrabotannykh i perspektivnykh ploshchadiakh [Comprehensive geophysical study of potentially hazardous areas of the waterproof layer in undermined and promising areas]. Perm': GI UrO RAN, 2009.
36. Koskov V.N., Koskov B.V. Geofizicheskie issledovaniia skvazhin i interpretatsiia dannykh GIS [Well logging and well logging data interpretation]. Perm': Permskii gosudarstvennyi tekhnicheskii universitet, 2007, 317 p.
37. Koskov V.N. Interpretatsiia dannykh GIS na baze sistemno-strukturnogo podkhoda [Interpretation of well logging data based on a system-structural approach]. Perm': Permskii gosudarstvennyi tekhnicheskii universitet, 2012, 140 p.
38. Kostitsyn V.I., Khmelevskoi V.K. Geofizika [Geophysics]. Perm': Permskii natsional'nyi issledovatel'skii politekhnicheskii universitet, 2018, 428 p.
39. Kudriashov A.I. Verkhnekamskoe mestorozhdenie solei [Verkhnekamskoe salt deposit]. Moscow: EPSILONPLUS, 2013, 2nd ed, 371 p.
40. Kudriashov A.I. Mineral'no-syr'evye resursy Permskogo kraia: Entsiklopediia [Mineral resources of the Perm region: Encyclopedia]. Moscow: Krasnaia ploshchad', 2006, 464 p.
41. Malysheva M.G., Vendel'shtein B.Iu., Tuzov V.P. Obrabotka i interpretatsiia materialov geofizicheskikh issledovanii skvazhin [Processing and interpretation of well logging data]. Moscow: Nedra, 1990, 312 p.
42. Ermakov G.I., Fominykh V.I., Krasnoshtein A.E. et al. Analiz avariinoi situatsii na Vtorom Solikamskom rudnike [Analysis of the emergency situation at the Second Solikamsk mine]. *Problemy bezopasnosti pri ekspluatatsii mestorozhdenii poleznykh iskopaemykh v zonakh gradopromyshlennykh aglomeratsii. Tezisy dokladov mezhdunarodnogo simpoziuma*. Perm': UrO RAN, 1995, pp. 47-48.
43. Petrotektonicheskie osnovy bezopasnoi ekspluatatsii Verkhnekamskogo mestorozhdeniia kaliino-magnievykh solei [Petrotectonic foundations for the safe exploitation of the Verkhnekamskoye potassium-magnesium salt deposit]. Ed. doktor geologo-mineralogicheskikh nauk N.M. Dzhinoridze. Solikamsk: OGUP Solikamsk, tipografiia, 2000, 400 p.
44. Kudriashov A.I., Vasiukov V.E., Fon-der-laass G.S. et al. Razryvnaia tektonika Verkhnekamskogo mestorozhdeniia solei [Fracture tectonics of the Verkhnekamsk salt deposit]. Ed. A.I. Kudriashov. Perm': GI UrO RAN, 2004, 194 p.
45. Sashurin A.D. Geomekhanika v gornom dele: fundamental'nye i prikladnye issledovaniia [Geomechanics in Mining: Fundamental and Applied Research]. *Gornyi zhurnal*, 2012, no. 1, pp. 29-32.

Библиографический список

1. Сейсморазведочные исследования водозащитной толщи Верхнекамского месторождения калийных солей / И.А. Санфиров, А.И. Бабкин, Г.Ю. Прийма, А.Г. Ярославцев, А.М. Пригара, К.Б. Фатькин // Горный журнал. – 2008. – № 10. – С. 45–48.
2. Малоглубинные геофизические исследования на Верхнекамском месторождении калийных солей / И.А. Санфиров, Ю.И. Степанов, К.Б. Фатькин, И.Ю. Герасимова, А.И. Никифорова // Физико-технические проблемы разработки полезных ископаемых. –2013. – № 6. – С. 71–77.
3. Sanfirov I.A., Babkin A.I., Baybakova T.V. Seismic CDP profiling in wells // 13^{TH} conference and exhibition on engineering geophysics. Engineering Geophysics. – 2007.
4. Integrated Interpretation of Ground-Based and Mine Seismic Surveys in The Potash Deposit Areas with a Complicated Geological Structure / A.I. Nikiforova, I.A. Sanfirov, V.M. Nezdanov, R.A. Bogdanov // Conference Proceedings, Engineering and Mining Geophysics 2021. – 2021. – Vol. 2021. – P. 1–7. DOI: 10.3997/2214-4609.202152109
5. Царев Р.И. Обоснование выбора модели геологической среды при решении прямой задачи сейсморазведки МОВ ОГТ на ВКМС // Геофизика. – 2018. – No. 5. – С. 18–23.
6. Способ шахтной сейсморазведки для изучения особенностей геологического строения ВКМС / А.А. Жуков, А.М. Пригара, Р.И. Царев, И.Ю. Шусткина // ГИАБ. – 2019. – № 4. – С. 121–13.
7. Указания по защите рудников от затопления и охране подрабатываемых объектов на Верхнекамском месторождении калийно-магниевых солей / ГИ УрО РАН. – СПб. – Пермь, 2014. – 130 с.
8. Методические рекомендации к «Указаниям по защите рудников от затопления и охране подрабатываемых объектов на Верхнекамском месторождении калийно-магниевых солей» / ГИ УрО РАН. – СПб. – Пермь, 2014. – 66 с.
9. Барях А.А., Асанов В.А., Паньков И.Л. Физико-механические свойства соляных пород Верхнекамского калийного месторождения: учеб. пособие для вузов. – Пермь: ПГТУ, 2008. – 199 с.

10. Барях А.А., Константинова С.А., Асанов В.А. Деформирование соляных пород. – Свердловск: Изд-во УрО РАН, 1996. – 180 с.
11. The increasing of exploitation safety of potassium salt deposit based on geological-geomechanical simulation / Yu. Kashnikov, A. Ermashov, D. Shustov, D. Khvostantcev // EUROCK 2018: Geomechanics And Geodynamics Of Rock Masses. – 2018. – Vol. 2. – P. 1425–1430.
12. Кашников Ю.А., Ермашов А.О., Ефимов А.А. Геолого-геомеханическая модель участка Верхнекамского калийного месторождения // Записки Горного института. – 2019. – Т. 237. – С. 259–267.
13. Создание геолого-геомеханической модели Верхнекамского месторождения калийных солей / Ю.А. Кашников, А.О. Ермашов, Д.В. Шустов, О.О. Лебедева // Маркшейдерский вестник. – 2019. – № 1 (128). – С. 39–45.
14. Kashnikov Yu.A., Shustov D.V., Ermashov A.O. Solving the problems of exploitation safety of potassium salt deposit based on joint application of geophysical and geomechanical studies // EUROCK 2021: Mechanics and Rock Engineering, from Theory to Practice 20-25 September. – Turin, Italy, 2021.
15. Геолого-геомеханическая модель Астраханского газоконденсатного месторождения / Ю.А. Кашников, С.В. Гладышев [и др.] // Газовая промышленность. – 2012. – № 3. – С. 29–33.
16. 3D geological geomechanical reservoir modeling for the purposes of oil and gas field development optimization / D.V. Shustov, Yu.A. Kashnikov, S.G. Ashikhmin, A.E. Kukhtinskiy // EUROCK 2018: Geomechanics And Geodynamics Of Rock Masses. – 2018. – Vol. 2. – P. 1425–1430.
17. Zoback M.D. Reservoir Geomechanics. – Cambridge. University Press, 2007. – P. 449.
18. Кашников Ю.А., Ашихмин С.Г. Механика горных пород при разработке месторождений углеводородного сырья. – М.: Горная книга, 2019. – 496 с.
19. Various effect of faults on mechanical earth models: A case study of integrated study / S. Khatibi, M. Ostadhassan, A. Aghajanpour, Yu. Kovaleva, R. A. Mohammed // Geomechanics and Geodynamics of Rock Masses. – Taylor & Francis Group. – London, 2018. – P. 1395–1399.
20. Plumb R.A. Influence of composition and texture on the failure properties of clastic rocks // SPE/ISRM 28022. In: Proc. Eurock '94. Delft, Netherlands, 29–31 August 1994. – 1994. – P. 13–20.
21. Empirical relations between rock strength and physical properties in sedimentary rocks / C. Chang, M.D. Zoback [et al.] // Journal of Petroleum Science and Engineering. – 2006. – Vol. 51. – P. 223–237.
22. Sone H. Mechanical properties of shale gas reservoir rocks and its relation to the in-situ stress variation observed in shale gas reservoirs: Phd thesis. – 2012.
23. Cuervo S., Adachi J., Lombardo E. Integration of 1D and 3D Mechanical Earth Models in oil shale plays. An example from the Vaca Muerta Formation (Argentina) // 52nd U.S. Rock Mechanics/Geomechanics Symposium, ARMA, 2018.
24. Шустов Д.В., Кашников Ю.А. Разработка геолого-геомеханической модели участка Юрубчено-Тохомского месторождения // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2015. – № 4. – С. 26–31.
25. Геомеханические характеристики терригенных продуктивных объектов нефтяных месторождений Западного Урала / Ю.А. Кашников, Д.В. Шустов, А.Э. Кухтинский, С.А. Кондратьев // Нефтяное хозяйство. – 2017. – № 4. – С. 32–35.
26. Чертенков М.В., Рузин Л.М. Предпосылки для комплексного использования стандартного каротажа и акустических исследований с целью прогноза коэффициента Пуассона. // Нефтяное хозяйство. – 2017. – № 1. – С. 16–18.
27. Barree R. A Composite Determination of Mechanical Rock Properties for Stimulation Design (What to do When You Don't Have a Sonic Log) // SPE 108139 presented at the 2007 SPE Rocky Mountain Oil & Gas Technology Symposium. – Denver, Colorado, U.S.A. – 2007.
28. Eissa E.A., Kazi A. Relation between static and dynamic Young's moduli of rocks // Int. J. Rock Mech. – 1988. – Vol. 25. – P. 479–482.
29. Petroleum Related Rock Mechanics / E. Fiaer, R.M. Holt, P. Horsrud [et al.] – 2 ND Edition. – Elsevier, 2008. – P. 391–434.
30. ГОСТ 21153.2-84. Породы горные. Методы определения предела прочности при одноосном сжатии. – М.: Издательство стандартов, 1985. – 10 с.
31. ГОСТ 28985-91. Породы горные. Методы определения деформационных характеристик при одноосном сжатии. – М.: Издательство стандартов, 1991. – 19 с.
32. ГОСТ 21153.8-88. Породы горные. Методы определения предела прочности при объемном сжатии. – М.: Издательство стандартов, 1988. – 10 с.
33. Wittke W. Rock Mechanics Based on an Anisotropic Jointed Rock Model. – Ernst & Sohn Verlag, 2014. – 876 s.
34. Ermashov A.O., Lebedeva O.O., Rysin A.I. The analysis of interbed stability with mathematical modeling methods // Topical Issues of Rational Use of Natural Resources 2019. – 2020. – Vol. 1. – P. 173–182. DOI: 10.1201/9781003014577-22
35. Барях А.А. Комплексное геофизическое исследование потенциально-опасных участков ВЗТ на подработанных и перспективных площадях. – Пермь: ГИ УрО РАН, 2009.
36. Косков В.Н., Косков Б.В. Геофизические исследования скважин и интерпретация данных ГИС: учеб. пособие. – Пермь: Изд-во Перм. гос. техн. ун-та, 2007. – 317 с.
37. Косков В.Н. Интерпретация данных ГИС на базе системно-структурного подхода: учеб. пособие – Пермь: Изд-во Перм. гос. техн. ун-та, 2012. – 140 с.
38. Костицын В.И., Хмелевской В.К. Геофизика: учебник / Перм. гос. нац. исслед. ун-т. – Пермь, 2018. – 428 с.
39. Кудряшов А.И. Верхнекамское месторождение солей. – М.: EPSILONPLUS, 2013. – 2-е изд. – 371 с.
40. Кудряшов А.И. Минерально-сырьевые ресурсы Пермского края: Энциклопедия. – М.: Красная площадь, 2006. – 464 с.
41. Малышева М.Г., Вендельштейн Б.Ю., Тузов В.П. Обработка и интерпретация материалов геофизических исследований скважин. – М.: Недра, 1990. – 312 с.
42. Анализ аварийной ситуации на Втором Соликамском руднике / Г.И. Ермаков, В.И. Фоминых, А.Е. Красноштейн [и др.] // Проблемы безопасности при эксплуатации месторождений полезных ископаемых в зонах градопромышленных агломераций: тез. докл. междунар. симп. – Пермь: УрО РАН, 1995. – С. 47–48.
43. Петротектонические основы безопасной эксплуатации Верхнекамского месторождения калийно-магниевых солей / под ред. д.г.-м.н. Н.М. Джиноридзе. – Соликамск: ОГУП Соликамск, типография, 2000. – 400 с.
44. Разрывная тектоника Верхнекамского месторождения солей / А.И. Кудряшов, В.Е. Васюков, Г.С. Фон-дер-лаасс [и др.]; под науч. ред. А.И. Кудряшова. – Пермь: ГИ УрО РАН, 2004. – 194 с.
45. Сашурин А.Д. Геомеханика в горном деле: фундаментальные и прикладные исследования // Горный журнал. – 2012. – № 1. – С. 29–32.

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