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Kydrashov Adilzhan Bekezhanovich*[1],
PhD, acting associate professor,
West Kazakhstan Agrarian-Technical University,
Republic of Kazakhstan, 090009, Oral, Zhangir khan street., 51/2,
a.kydrashov@mail.ru, ORCID ID: 0000-0002-1404-1589

Amangeldiyev Alisher Kasymuly[2],
master of Technical sciences, teacher,
West Kazakhstan Agrarian-Technical University,
Republic of Kazakhstan, 090009, Oral, Zhangir khan street., 51/2,
alisher.amangeldiyev.99@mail.ru, ORCID ID: 0009-0001-9598-5345

Tazhen Temirlan Bauyrzhanuly[3],
master student,
West Kazakhstan Agrarian-Technical University,
Republic of Kazakhstan, 090009, Oral, Zhangir khan street., 51/2,
tazhen02@bk.ru, ORCID ID: 0009-0004-3051-5918

Kubayev Bauyrzhan Serzhanovich[4],
master student,
West Kazakhstan Agrarian-Technical University,
Republic of Kazakhstan, 090009, Oral, Zhangir khan street., 51/2,
k.bauyr88@mail.ru, ORCID ID: 0009-0006-0187-9266

Seijalilov Ramil Denisovich [5],
master student,
West Kazakhstan Agrarian-Technical University,
Republic of Kazakhstan, 090009, Oral, Zhangir khan street., 51/2,
star.ramil@bk.ru, ORCID ID: 0009-0006-8607-2700

GEOMECHANICAL NUMERICAL MODELING IN THE STUDY OF THE STRESS-STRAIN STATE OF THE BOREHOLE ZONE

Abstract. This article examines current geomechanics issues related to numerical modeling of stress-strain states in the near-wellbore zone during oil and gas field development. Methods for stress field analysis are presented to identify potential failure zones for structural components of the main casing string and wellbore perforations. An example of calculating reservoir permeability using effective conditional stress modeling in the near-wellbore zone for wellbores is provided. The research is illustrated by an analysis of calculation results based on the finite element method using CAE programs and mechanical properties of rock masses taken from each field. The rock mass stress is calculated using the Mohr-Coulomb criterion, and the results are compared. Modeling of the stress-strain state in the near-wellbore zone showed that in the case of a partial absence of cement stone in the casing, failure zones can occur due to tensile and compressive stresses, which increases the likelihood of accidents during well operation. It is shown that the considered methods and numerical models of near-wellbore zones can be used in the future, and the assessment of near-wellbore stresses can be used to justify the parameters of wells in other oil and gas fields.

Key words. Numerical modeling, finite element method, stress-strain state, destruction zone, permeability, Mohr-Coulomb criterion.

Қыдырашов Әділжан Бекежанұлы[*1],
техника ғылымдарының кандидаты, доцент м.а.,
Батыс Қазақстан аграрлық-техникалық университеті,
Қазақстан Республикасы, 090009, Орал қаласы, Жәңгір хан көшесі, 51/2,
a.kydrashov@mail.ru, ORCID ID: 0000-0002-1404-1589

Амангелдиев Әлішер Қасымұлы[2],
техника ғылымдарының магистрі, оқытушы,
Батыс Қазақстан аграрлық-техникалық университеті,
Қазақстан Республикасы, 090009, Орал қаласы, Жәңгір хан көшесі, 51/2,
alisher.amangeldiyev.99@mail.ru, ORCID ID: 0009-0001-9598-5345

Тәжен Темірлан Бауыржанұлы[3],
магистрант,
Батыс Қазақстан аграрлық-техникалық университеті,
Қазақстан Республикасы, 090009, Орал қаласы, Жәңгір хан көшесі, 51/2,
tazhen02@bk.ru, ORCID ID: 0009-0004-3051-5918

Кубаев Бауыржан Сержанұлы[4],
магистрант,
Батыс Қазақстан аграрлық-техникалық университеті,
Қазақстан Республикасы, 090009, Орал қаласы, Жәңгір хан көшесі, 51/2,
k.bauyr88@mail.ru, ORCID ID: 0009-0006-0187-9266

Сейджалилов Рамиль Денисович[5],
магистрант,
Батыс Қазақстан аграрлық-техникалық университеті,
Қазақстан Республикасы, 090009, Орал қаласы, Жәңгір хан көшесі, 51/2,
star.ramil@bk.ru, ORCID ID: 0009-0006-8607-2700

ҰҢҒЫМА МАҢЫНДАҒЫ АЙМАҚТЫҢ КЕРНЕУЛІ ДЕФОРМАЦИЯЛЫ КҮЙІН ЗЕРТТЕУДЕ ГЕОМЕХАНИКАЛЫҚ САНДЫҚ МОДЕЛДЕУ

Аңдатпа. Бұл мақалада мұнай және газ кен орындарын игеру кезінде ұңғыма маңындағы аймақтағы кернеулі деформациялық күйлерді сандық модельдеуге байланысты геомеханиканың кейбір өзекті мәселелері қарастырылады. Ұңғыма оқпанының негізгі шегендеу бағанасының құрылымдық элементтері мен перфорация арналарының ықтимал бұзылу аймақтарын анықтау үшін кернеу өрісін талдау үшін әдістер ұсынылған. Саңылау тесіктері үшін ұңғыма маңындағы кернеуді тиімді шартты моделдеу кезінде қабаттың өткізгіштігін есептеуге мысал келтірілген. Әр кен орыннан алынған тау жынысының механикалық қасиеттерін қолдана отырып, CAE бағдарламалармен соңғы элементтер әдісіне негізделген есептеп нәтижелерін анализдеп ғылыми еңбекте иллюстрация көрініс тапқан. Тау-кен массивінің кернеуі Мор - Кулон критериясы тарапынан есептелген және нәтижелері салыстырмалы түрде қарастырылған. Ұңғыма маңын кернеулі – деформациялы күйін модельдеу бағанда цемент тасы ішінара болмаған жағдайда созылу және қысу кернеулерінен бұзылу аймақтары пайда болуы мүмкін екенін көрсетті, бұл ұңғымаларды пайдалану кезінде апаттық жағдайлардың пайда болу ықтималдығын арттырады. Қарастырылған әдістер және ұңғыма маңындағы аймақтардың сандық модельдерін болашақта қолдануға болады, ұңғыма маңындағы кернеулерді бағалау басқа мұнай және газ кен орындарындағы ұңғыманың параметрлерін негіздеу мақсатында қолдануға болатындығы көрсетілген.

Кілт сөздер. Сандық модельдеу, шекті элементтер әдісі, кернеулі-деформациялы күйі, бұзылу аймағы, өткізгіштік, Мор-Кулон критериясы.

Кыдрашов Адильжан Бекежанович[*1],
кандидат технических наук, и.о. доцента,
Западно-Казахстанский аграрно-технический университет,
Республика Казахстан, 090009, г. Орал, ул. Жангир хана, 51/2,
a.kydrashov@mail.ru, ORCID ID: 0000-0002-1404-1589

Амангельдиев Алишер Касымулы[2],
магистр технических наук, преподаватель,
Западно-Казахстанский аграрно-технический университет,
Республика Казахстан, 090009, г. Орал, ул. Жангир хана, 51/2,
alisher.amangeldiyev.99@mail.ru, ORCID ID: 0009-0001-9598-5345

Тажен Темирлан Бауыржанулы[3],
магистрант,
Западно-Казахстанский аграрно-технический университет,
Республика Казахстан, 090009, г. Орал, ул. Жангир хана, 51/2,
tazhen02@bk.ru, ORCID ID: 0009-0004-3051-5918

Кубаев Бауыржан Сержанович[4],
магистрант,
Западно-Казахстанский аграрно-технический университет,
Республика Казахстан, 090009, г. Орал, ул. Жангир хана, 51/2,
k.bauyr88@mail.ru, ORCID ID: 0009-0006-0187-9266

Сейджалилов Рамиль Денисович[5],
магистрант,
Западно-Казахстанский аграрно-технический университет,
Республика Казахстан, 090009, г. Орал, ул. Жангир хана, 51/2,
star.ramil@bk.ru, ORCID ID: 0009-0006-8607-2700

ГЕОМЕХАНИЧЕСКОЕ ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПРИ ИССЛЕДОВАНИИ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ОКОЛОСКВАЖИННОЙ ЗОНЫ

Аннотация. В данной статье рассматриваются актуальные вопросы геомеханики, связанные с численным моделированием напряженно-деформированного состояния в прискважинной зоне при разработке нефтяных и газовых месторождений. Представлены методы анализа поля напряжений для выявления возможных зон разрушения конструктивных элементов основной обсадной колонны и перфорационных каналов ствола скважины. Приведен пример расчета проницаемости пласта при эффективном условном моделировании напряжений в прискважинной зоне для стволов скважин. Научная работа иллюстрируется анализом результатов расчетов на основе метода конечных элементов с использованием CAE-программ с использованием механических свойств горной породы, взятых с каждого месторождения. Проведен расчет напряженности массива горных пород по критерию Мора-Кулона и проведено сравнение результатов. Моделирование НДС в прискважинной зоне показало, что в случае частичного отсутствия цементного камня в колонне возможно возникновение зон разрушения за счет растягивающих и сжимающих напряжений, что увеличивает вероятность возникновения аварий при эксплуатации скважин. Показано, что рассмотренные методы и численные модели околоскважинных зон могут быть использованы в дальнейшем, а оценка околоскважинных напряжений может быть использована для обоснования параметров скважин на других нефтяных и газовых месторождениях.

Ключевые слова. Численное моделирование, метод конечных элементов, напряженно-деформированное состояние, зона разрушения, проницаемость, критерий Кулона–Мора.

Introduction. In recent years, more and more attention has been paid to the problems of geomechanics in the development of oil and gas fields. Determining the reliable stress-strain state of the reservoir and well design allows one to avoid emergency situations during drilling, construction and operation of wells, increase the efficiency of creating hydraulic fracturing cracks in the reservoir, prevent intense sand production for weakly cemented reservoirs, study the transformation of the stress field when creating perforation channels, predict variations in filtration-capacitive properties (FCP) with an increase or decrease in fluid pressure in the reservoir and near the well, etc. [1,2,3,4]. Currently, methods for creating 1D geomechanical models of wells and 3D models of fields are widely used [5,6]. The relevance of their application is beyond doubt, however, these models have their limitations. In particular, they do not allow for a full consideration of all the structural elements of the well (column, cement stone), an assessment of the probability of casing failure in the presence of intervals of absence of cement stone behind the casing, a study of the well stability during the hardening of the cement slurry, a prediction of the transformation of the non-uniform stress field near the perforation channels, etc.

Solving such problems requires creating special numerical models of borehole zones that allow for taking into account the geometric features of the borehole structure and voids near it (perforation channels, intervals without cement stone, etc.), as well as conducting a full-fledged analysis of the stress field for subsequent prediction of the occurrence of possible failure zones in the column, support or rock, and variations in the reservoir properties of reservoir rocks [7,8,9]. This publication examines a number of geomechanics problems related to calculating the stress-strain state (SSS) of the rock mass and borehole using the finite element method. The main results of the performed modeling are presented, and the main most significant conclusions related to increasing the efficiencies of oil and gas field development using geomechanical calculations are formulated.

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Research materials and methods. Examples of calculation and analysis of stresses in the near-wellbore zone. In numerical modeling of the SSS, differential relations are used to describe the elastic and poroelastic behavior of a solid. Due to the use of the variational principle and the law of conservation of energy, differential relations are transformed into systems of linear equations that are solved by a numerical method. Below are considered some of the most relevant numerical models with the main results.

Results and discussion.

Modeling of changes in the SSS and permeability of reservoir rocks when creating slot perforation. During the modeling, a finite element scheme of a section of a vertical well was used, presented in Illustration 1. The height of the model was 0.75 m, the radius was 5 m, the radius of the open wellbore was 0.108 m. 4 slot channels were simulated, shifted along the circumference by 90°, due to the symmetry it is sufficient to use a sector of the model in the form of a quarter of a cylinder. The channels had a horizontal cross-section in the form of an ellipse with radii of 0.4 and 0.02 m. In this model, the column and cement stone were not taken into account, but it was assumed that filtration through the walls of the well is absent and occurs only through the walls of the slot perforation.

Table 1 presents the geomechanical properties of the reservoir rock and the pressure values. The creation of a depression on the formation of 2–8 MPa in the well was simulated;

the calculations were made using the example of a terrigenous reservoir of one of the oil fields in the north of the West Kazakhstan region.

1 Table - Mechanical properties of rock and pressure values used in calculations

№	Characteristics	Value
1	Elastic modulus, GPa	20.00
2	Poisson's ratio, units	0.17
3	Biot's coefficient, units	0.85
4	Ultimate strength under uniaxial compression, MPa	24.00
5	Angle of internal friction, degrees	28.00
6	Permeability, mD	99.00
7	Formation depth, m	4400.00
8	Vertical stress, MPa	41.00
9	Horizontal stress, MPa	33.00
10	Formation pressure, MPa	16.00
11	Formation depression, MPa	2–8

It was assumed that with a change in effective stresses, permeability decreases due to rock compaction. To determine the permeability value, the dependence given in the publication [10] was used:

$$\begin{cases} K = K_0 - \lambda\Delta\sigma, \ \Delta\sigma \geq 0 \\ K = K_0 + \kappa\Delta\sigma, \ \Delta\sigma < 0 \end{cases}$$

where

K_0 − initial permeability of the formation, mD;

K − current permeability, mD;

$\Delta\sigma$ − change in average effective stress, MPa;

λ − permeability reduction coefficient, mD/MPa;

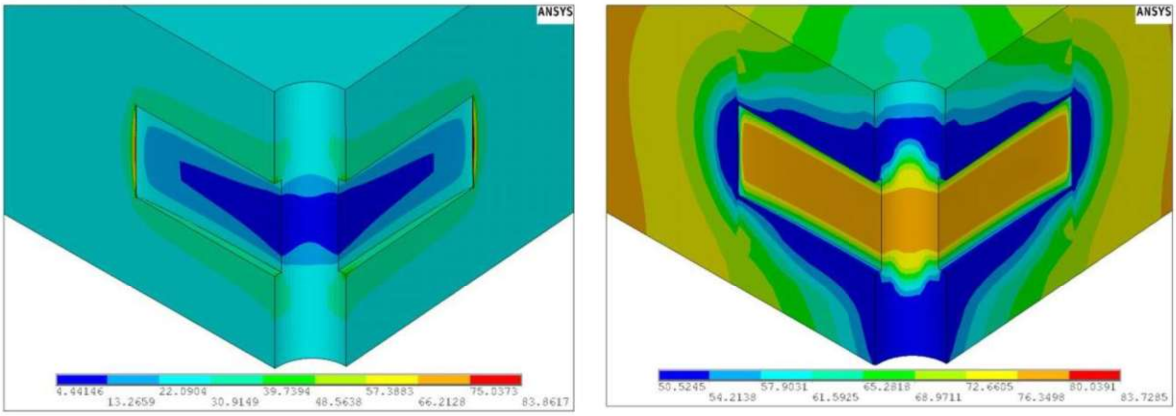
κ − permeability recovery coefficient, mD/MPa.

To assess the destruction zones, the Mohr-Coulomb criterion was used in the following form:

$$\sigma_1 - p = \sigma_c + (\sigma_3 - p)\frac{1+\sin\varphi}{1-\sin\varphi},$$

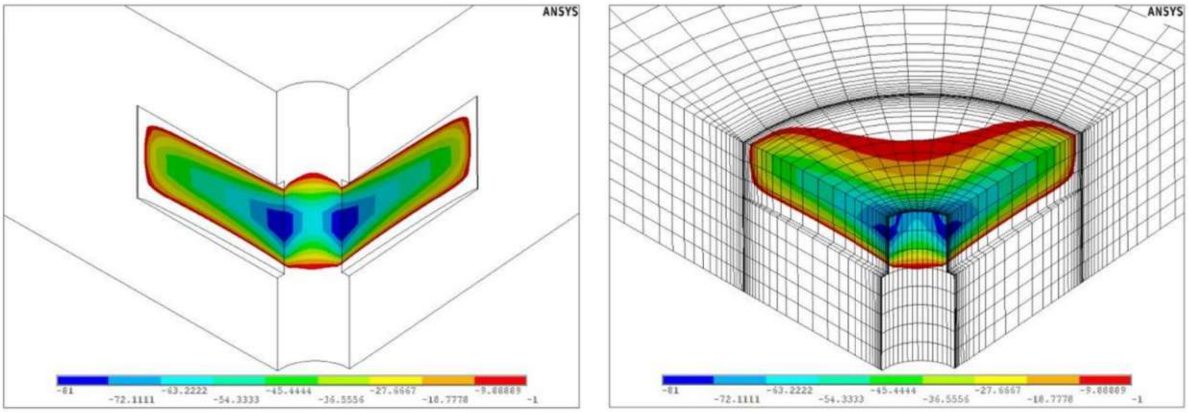
where
σ_1, σ_3 − principal maximum and minimum stresses, respectively, MPa;
σ_c − ultimate strength of rock under uniaxial compression, MPa;
φ − angle of internal friction, deg;
p − formation pressure, MPa.

As a result of the calculations, the distribution fields of effective stresses were obtained for different degrees of depression on the formation. Illustrations 2–4 shows some of the main results of the calculations.



a b

Figure 2 - Distribution of average effective stresses in MPa (a) and permeability in mD (b) near the well when creating slot perforation for a depression of 5 MPa



a b

Figure 3 - Distribution of the magnitude of change in effective stresses (in %) in the model as a whole (a) and on the section along the middle of the cracks (b) near the well when creating a slot perforation for a depression of 5 Mpa

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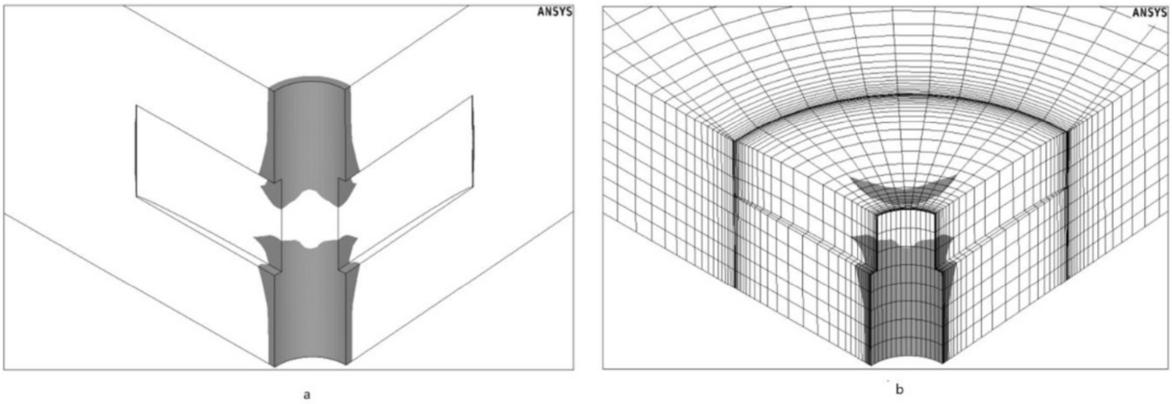


Figure 4 - Areas of destruction (plastic deformation) of the reservoir rock according to the Mohr-Coulomb criterion as a whole in the model (a) and on the section along the middle of the cracks (b) near the well when creating a slot perforation for a depression of 5 Mpa

As a result of these calculations, the following main conclusions were made:

1. Based on the obtained stress distribution field (Illustration. 2, 3), they are shown to be significantly restored (reduced) when creating slit perforation, which leads to the restoration of the reservoir rock permeability. The area of stress restoration is located near the well within a radius equal to the length of the slits.
2. Using the dependence of permeability change on effective stresses, the distribution of this reservoir rock characteristic under the influence of the changing stress state of the formation was determined. The results of the calculations showed that the most intensive permeability restoration occurs on the lateral surfaces of the slits (see Illustration. 2b).
3. Evaluation of the rock destruction area after creating this type of perforation using the Mohr-Coulomb criterion showed that the perforation cracks are sufficiently resistant to the effects of stress and areas of plastic deformations occur only near the well (see Illustration. 4).

Modeling of reservoir rock stress-strain state when creating cumulative perforation.

During the modeling, a finite element scheme of a vertical well section was used, shown in Illustration. 5. The height of the model was 0.167 m, the radius was 3 m, the radius of the open wellbore was 0.108 m. 4 cumulative perforation holes were simulated, shifted along the circumference by 90°, due to symmetry, it is sufficient to use a model sector in the form of a quarter of a cylinder. The channels were set in the form of an ellipsoid with radii of 0.3 and 0.06 m.

In this model, the column and cement stone were also not taken into account, but it was assumed that filtration through the well walls is absent and is carried out only through the walls of the perforation channels.

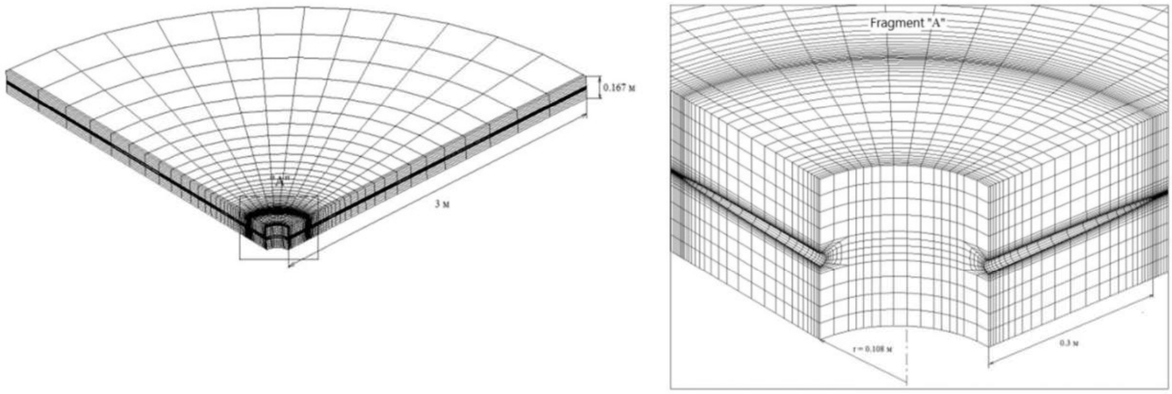


Figure 5 - Finite element scheme of the near-wellbore zone, used to model the change in the stress-strain state during the creation of cumulative perforation

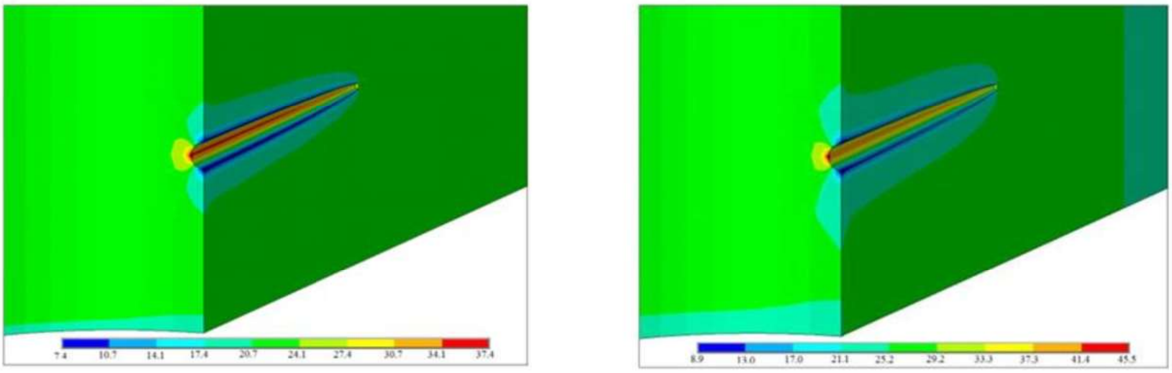
Table 2 presents the geomechanical properties of the reservoir rock and the pressure values.

The creation of a depression in the well of 2-10 MPa on the formation was simulated, the calculations were made using the example of carbonate reservoirs of two oil fields in the north of West Kazakhstan Region.

2 Table - Mechanical properties of the rock and the pressure values used in the calculations

№	Characteristics	Rozhkovskoye field	Chinarevskoye field
1	Elastic modulus, GPa	30.00	28.00
2	Poisson's ratio, units	0.3	0.30
3	Biot's coefficient, units	0.55	0.60
4	Ultimate strength under uniaxial compression, MPa	35.00	30
5	Angle of internal friction, degrees	32.00	30
6	Permeability, mD	98.00	100.00
7	Formation depth, m	1680.00	1790.00
8	Vertical stress, MPa	42.00	45.00
9	Horizontal stress, MPa	24.00	25.60
10	Formation pressure, MPa	17.50	18.60
11	Formation depression, MPa	2–10	2-10

As a result of the calculations, distribution fields of effective stresses were obtained for different depression values on the formation. Then the stress values were analyzed for the occurrence of destruction zones based on the application of the Coulomb-Mohr criterion. Illustrations 6 and 7 illustrate some of the main results of the calculations.



a b

Figure 6 - Distribution of average effective stresses in MPa near the well when creating cumulative perforation for Chinarevskoye field at a depression of 2 MPa (a) and 10 MPa (b)

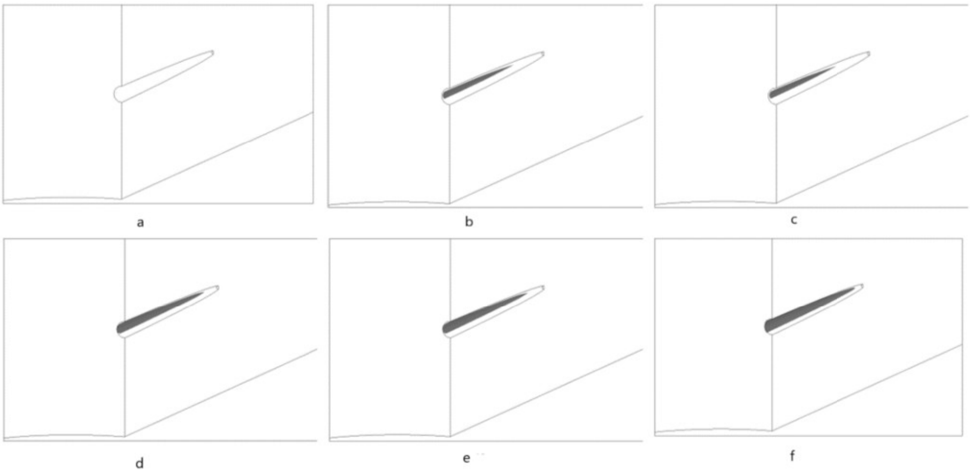


Figure 7 - Dynamics of reservoir rock destruction zones near holes
Cumulative perforation according to the Mohr-Coulomb criterion, for oil fields of the Rozhkovskoye (a, c, e) and Chinarevskoye (b, d, f) fields at a depression of 2 MPa (a, b), 6 MPa (c, d) and 10 MPa (e, f)

Based on the results of these calculations, the following main conclusions were made:

1. Based on the obtained stress field, it was shown that near the perforation channels, the area of increasing stresses is comparable with the area of decreasing stresses, which suggests that significant permeability recovery with this type of perforation is unlikely to be possible.
2. Evaluation of the destruction areas according to the Mohr-Coulomb criterion revealed that when creating cumulative perforation, destruction zones near the holes can occur already at a depression of 2 MPa, which can lead to negative consequences, in particular, to clogging of the perforation channels and a reduction in the amount of fluid flow into the well.
3. The developed numerical finite element model of the near-wellbore zone can be used in the future to calculate the non-uniform stress field when opening layers by cumulative perforation using the example of other productive objects of oil and gas fields.

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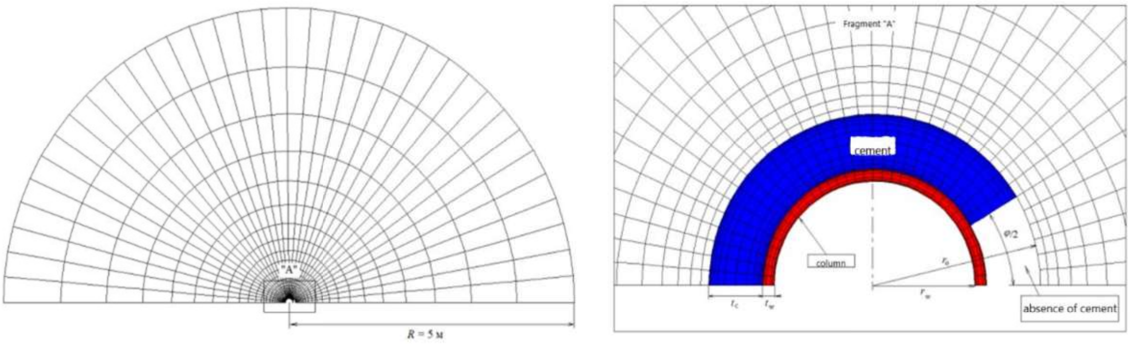
Modeling the SSS of the well structure and determining the stability of the production string under conditions of partial absence of cement stone.

To calculate the stress field a flat finite element scheme was created, including: a casing string, cement stone with an area of its absence, a section of reservoir rock near a vertical well with a radius of 5 m (Illustration 8). Due to symmetry, only half of the selected cross-section of the near-wellbore zone was considered. Illustration 8 shows the finite element scheme of the model used in the calculations.



R – radius of the model, r_o – radius of the open borehole, r_w – inner radius of the column, t_c – thickness of the cement stone, t_w – thickness of the column

Figure 8 - Finite element diagram of the section of the near-wellbore zone, used to calculate the stability of the column in conditions of partial absence of cement stone

Table 3 summarizes the initial physical characteristics of the model using the example of the Zhanazhol deposit of one of the fields of the Aktobe region: the physical and mechanical properties of the rocks and the production string, as well as the values of the external stresses affecting the model.

3 Table - Physical characteristics of the model used in calculations

№	Characteristics	Value
1	Modulus of elasticity of rock, GPa	40.00
2	Poisson's ratio of rock, units	0.22
3	Modulus of elasticity of cement, GPa	12.20
4	Poisson's ratio of cement, units	0.13
5	Modulus of elasticity of casing, GPa	200.00
6	Poisson's ratio of casing, units	0.20
7	Yield strength of column steel, MPa	539.00
8	Formation depth, m	3200.00
9	Vertical stress, MPa	70.40
10	Horizontal stress, MPa	52.00
11	Formation pressure, MPa	35.00

As a result of the calculations, stress distribution fields were obtained for different values of the angle of the cement-free sector. Then, the stress values were analyzed for the occurrence of zones of destruction in the column based on the yield strength of the column steel. Illustration 9 shows some of the main results of the calculations.

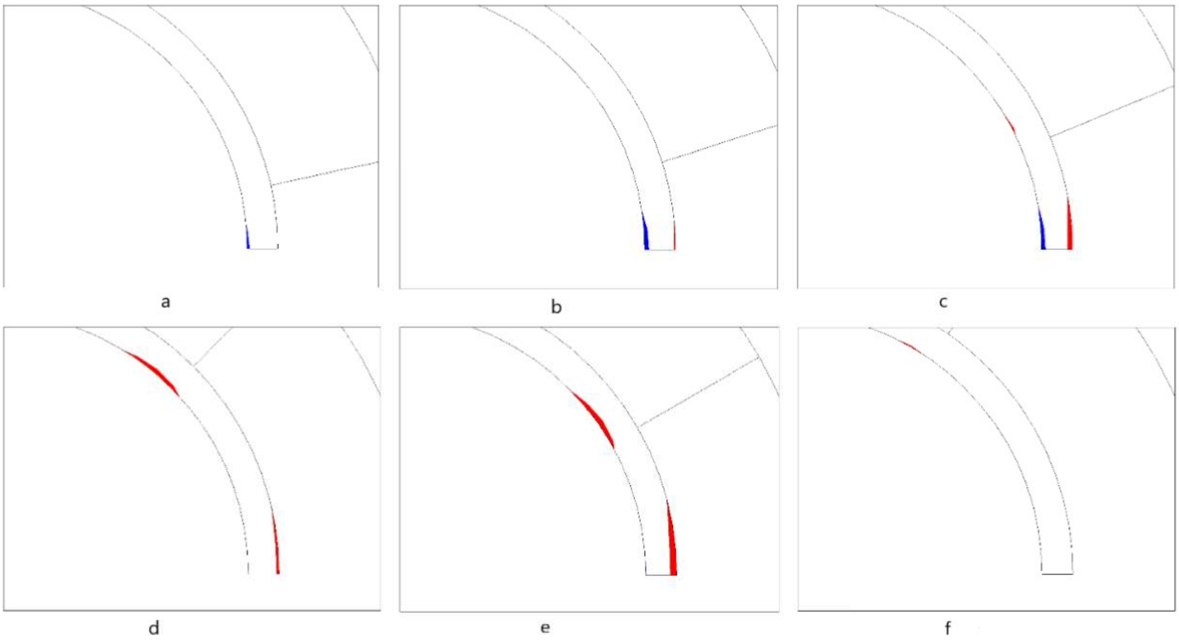


Figure 9 - Dynamics of destruction zones in the production casing due to its poor cementing for the sector of absence of cement stone with an angle: a – 25°; b – 35°; c – 45°; d – 60°; e – 90°; f – 110° (blue color – destruction from compressive loads, red – from tensile loads)

The calculations of stresses in the well structure in the conditions of partial absence of cement stone allowed us to draw the following main conclusions:

1. Numerical modeling showed that maximum stresses in the column arise when the pressure in the void space is minimal.

If the pressure in the interval of absence of cement stone is equal to the formation pressure, then it partially compensates for the pressure in the well, which leads to a decrease in stresses.

2. Based on the analysis of the areas of destruction of the production casing, it was concluded that plastic deformations in the column begin to appear at an angle of the sector of the void space of approximately 25°, while there are

areas of destruction from both tensile and compressive stresses. With increasing the sector angle of the void space, the damaged areas of the casing also first increase, and then begin to decrease and completely disappear for a sector angle greater than 110°.

3. Calculations have shown that for the considered conditions of modeling the formation and well design, the production string can be in a stable state even with a partial absence of cement stone in the annular space. At the same time, for each specific formation and each specific well design, its own calculation of the SSS and its analysis are required to determine the conditions for maintaining the integrity of the production string of the well.

Conclusion. The results obtained in this scientific work allow us to make the following main conclusions:

1. The article considers several examples of numerical modeling of the stress-strain state

near a well using the finite element method. The presented results were obtained using special numerical models of near-wellbore zones, taking into account their main structural elements and the geometry of voids near the well (perforation channels, intervals without cement stone).

2. Modeling of slot perforation channels showed that areas of unloading (reduction) of effective stresses arise near the holes, which should lead to restoration of the reservoir permeability and indicate the effectiveness of this perforation method.

3. Based on the calculations of the stress-strain state near cumulative perforation holes, it was shown that the destruction of their walls is possible even at small depressions on the formation, which indicates that the selection of optimal well operating modes requires preliminary calculations of the stress field that arises after cumulative perforation.

4. Modeling the stress-strain state of a well under conditions of partial absence of cement stone showed that areas of destruction from tensile and compressive stresses can occur in the column, which increases the likelihood of an emergency during well operation.

5. The considered methods and numerical models of near-wellbore zones can be used in the future to assess stresses near a well for development conditions of other oil and gas fields in order to select the most effective technology for completion and optimization of well operating parameters.

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