БЕЛОРУССКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ / BELARUSIAN STATE UNIVERSITY

УТВЕРЖДАЮ / APPROVED

Ректор Белорусского государственного университета/ Rector of Belarusian State University

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15.07.2024

Регистрационный/Registration № 2335/m.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ В ЗАДАЧАХ ПОДЗЕМНОЙ ГИДРОДИНАМИКИ

COMPUTER SIMULATION IN PROBLEMS OF UNDERGROUND HYDROMECHANICS

Учебная программа учреждения образования по учебной дисциплине для специальности:

The program of the educational institution of the discipline for the specialty:

Специальность / Speciality:

7-06-0533-06 Механика и математическое моделирование
7-06-0533-06 Mechanics and Mathematical Modelling

Профилизация / Profilization:

Теоретическая и прикладная механика
Theoretical and Applied Mechanics

2024 г.

Учебная программа составлена на основе ОСВО 7-06-0533-06-2023 и учебного плана БГУ № M54a-5.4-114/уч. от 11.04.2023.

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(протокол № 12 от 28.05.2024)

Научно-методическим советом БГУ
(протокол № 9 от 28.06.2024)

Заведующий кафедрой ____________________ М.А. Журавков

ПОЯСНИТЕЛЬНАЯ ЗАПИСКА

Цели и задачи учебной дисциплины

Цель учебной дисциплины:

– освоения основных идей и методов современной вычислительной гидромеханики и геофильтрации;

– подготовка специалистов, способных ставить и решать задачи в таких областях инженерной деятельности как нефтедобыча, расчет устойчивости гидрозащитных сооружений и дамб, проектирование водосливов, расчет ледопородных ограждений;

– развитие профессионального мышления, которое обеспечило бы будущему специалисту возможность свободно оперировать профессиональными знаниями, видеть проблемы и оптимальные пути их решения в самостоятельной практической деятельности.

Задачи учебной дисциплины:

– ознакомление магистрантов с теоретическими основами механики деформируемого твердого тела, гидромеханики, геофильтрации, термодинамики;

– ознакомление магистрантов с основными численными подходами решения прикладных задач подземной гидромеханики, такими как метод конечных элементов и метод дискретных элементов;

– ознакомление магистрантов с теоретическими основами вычислительной геометрии, алгоритмами формирования сеток конечных элементов;

– ознакомление магистрантов с современными численными пакетами для решения задач геофильтрации и геомеханики;

– формирование навыков решения прикладных инженерных задач с использование математических моделей механики сплошной среды и гидромеханики.

Место учебной дисциплины в системе подготовки специалиста с углубленным высшим образованием (магистра).

Дисциплина «Computer Simulation in Problems of Underground Hydromechanics» посвящена изучению математических и численных подходов, основанных на основных положениях механики сплошной среды и гидромеханики, к решению прикладных задач геомеханики и геофильтрации, таких как: моделирование напорного и безнапорного движения подземных флюидов, анализ обводнения и устойчивости водозащитных сооружений, расчет динамики грунтовых вод при техногенном воздействии на породный массив.

Учебная дисциплина входит **в модуль** «Computational modeling of Physical processes» компонента учреждения образования.

Дисциплина практико-ориентирована. Слушатели получаю практические навыки работы с пакетами численного моделирования. Изучаются теоретические практические вопросы создания клеточных и симплициальных моделей моделируемых трехмерных тел и поверхностей. Рассматриваются конкретные приложения и примеры решения задач: анализа устойчивости напорных дамб; расчет динамики обводнения подземных горизонтов; расчет динамики грунтовых вод при строительстве котлованов.

Учебная программа составлена с учетом межпредметных связей и программ по дисциплинам: «Partial differential equations», «Integral transforms and complex variable functions» «Continuum mechanics» и «Mechanics of advanced materials».

Требования к компетенциям

Освоение учебной дисциплины «Computer Simulation in Problems of Underground Hydromechanics» должно обеспечить формирование следующей **специализированной компетенции:**

SC. Use typical software modules for the analysis of the generated analytical models of the problems posed, methods of mathematical and algorithmic modeling in solving problems of mechanics.

В результате изучения дисциплины «Computer Simulation in Problems of Underground Hydromechanics» магистрант должен:

знать:

– проблематику составления математических моделей и постановки граничных задач для описания процесса движения подземных флюидов и их взаимодействия с вмещающими породами и граничными телами;

– проблематику численного решения сопряженных задач гидродинамики и геофильтрации;

уметь:

– правильно составлять системы дифференциальных уравнений, описывающих сопряженное поведения флюида и вмещающих горных пород;

– правильно формулировать граничные условия для сопряженных геомеханических и геофильтрационных процессов;

- получать численные решения для модельных задач и проводить анализ полученных результатов;

иметь навык:

– генерации клеточных и симплициальных моделей трехмерных тел и поверхностей.

Структура учебной дисциплины

Дисциплина изучается в 3 семестре. на изучение учебной дисциплины «Computer Simulation in Problems of Underground Hydromechanics» отведено для очной формы получения углубленного высшего образования: 90 часов, в том числе 36 аудиторных часа, из них: лекции (в том числе дистанционно) – 18 часов, лабораторные (в том числе дистанционно) – 18 часов.

Трудоемкость учебной дисциплины составляет 3 зачетные единицы.

Форма промежуточной аттестации – зачёт.

EXPLANATORY NOTE

Aim and tasks of the discipline

Aim of the discipline:

- mastering the basic ideas and methods of modern computational hydromechanics and geofiltration;

- training specialists capable of setting and solving problems in such areas of engineering as oil production, calculating the stability of hydraulic structures and dams, designing spillways, calculating ice walls;

- developing professional thinking that would provide the future specialist with the opportunity to freely operate professional knowledge, see problems and optimal ways to solve them in independent practical activities.

Tasks of the discipline:

- familiarizing graduate students with the theoretical foundations of mechanics of deformable solids, hydromechanics, geofiltration, thermodynamics;

- familiarizing graduate students with the main numerical approaches to solving applied problems of underground hydromechanics, such as the finite element method and the discrete element method;

- familiarizing graduate students with the theoretical foundations of computational geometry and algorithms for generating finite element meshes;

- familiarizing graduate students with modern numerical packages for solving problems of geofiltration and geomechanics;

- preparing of skills for solving applied engineering problems using mathematical models of continuum mechanics and hydromechanics

Place of the academic discipline in the system of training a specialist with higher education.

The discipline "Computer Simulation in Problems of Underground Hydromechanics" is devoted to the study of mathematical and numerical approaches based on the fundamental principles of continuum mechanics and hydromechanics to solving applied problems of geomechanics and geofiltration, such as: modeling of pressure and gravity flow of underground fluids, analysis of flooding and stability of water protection structures, calculation of groundwater dynamics under man-made impact on rock mass.

The academic discipline is part of the module «Computational modeling of Physical processes» educational institution component.

Connections with other academic disciplines, including those of the of higher educational institution component: «Partial differential equations», «Integral transforms and complex variable functions» «Continuum mechanics» и «Mechanics of advanced materials».

Requirements for competences

Mastering of the academic discipline «Computer Simulation in Problems of Underground Hydromechanics» should provide the formation of the following universal competence*:*

SC. Use typical software modules for the analysis of the generated analytical models of the problems posed, methods of mathematical and algorithmic modeling in solving problems of mechanics.

As a result of mastering the academic discipline, the student is expected to:

know:

- a method for creating mathematical models and setting boundary value problems to describe the process of movement of underground fluids and their interaction with host rocks and boundary bodies;
- a method for numerically solving the associated problems of hydrodynamics and geofiltration;

be able to:

- correctly compose systems of differential equations describing the conjugate behavior of fluid and host rocks;
- correctly formulate boundary conditions for conjugate geomechanical and geofiltration processes;
- obtain numerical solutions for model problems and analyze the results obtained;

have skills in:

– methods for generating cellular and simplicial models of three-dimensional bodies and surfaces.

Structure of the academic discipline

The discipline is studied in the 3 semester. In total for the study of the discipline «Computer Simulation in Problems of Underground Hydromechanics» is allocated for full-time higher education – 90 hours, including 36 in-class hours, of them: lectures – 18 hours, practical classes – 18 hours.

The labor intensity of the discipline is 3 credit units.

Form of certification – end-of-term test.

CONTENT OF THE STUDY MATERIAL

Section 1 Finite element's mesh generation

Topic 1.1 Computational geometry background

Uniform and Non-Uniform Meshes. Algebraic methods of mesh generation. Differential equation methods. Elliptic schemes. Hyperbolic schemes. Un-structured grid generation. The Delaunay Triangulation(DT). Voronoi Diagrams. Polygon Triangulation. Line Segment Intersection. The planar graph. The Doubly-Connected Edge List. Ruppert's algorithm of DT. Mesh genera-tion/refining in Tochnog. Local h-refinement. Global h-refinement (more elements). Global p-refinement (polynomial refinement).

Section 2 Computational mechanic and hydrodynamic

Topic 2.1 Tochnog introduction

Finite element method(FEM) foundation. FEM in 1D, 2D and 3D. Isoparametric finite elements. Springs, trusses, beams and contact-springs elements. Linear and quadratic simplex elements (triangles, tetrahedrons). Linear and quadratic prism elements. A full family of first to fourth order bar, quadrilateral and brick elements. Space and time discretization. Automatic time-stepping. Files used by Tochnog.

Topic 2.2 Material deformation and flow

Differential equation of material deformation and flow in Tochnog. Components of equation: material density, velocity, stress, expansion volume, convection and diffusion temperature. Nearly incompressible Navier Stokes formulation. Linear solid formulation. Elasticity. Boundary conditions. Tochnog examples.

Topic 2.3 Plasticity. Damage. Contact analysis

Elasto-Plasticity. CamClay plasticity model. Cap1 plasticity model. Cap2 plasticity model. Compression limiting plasticity model. di Prisco plasticity model. Damage Mazars model. Contact analysis. Contact with and without friction. Frictional heat generation. Penalty formulation. Penalty velocity, pressure and temperature. Tochnog examples.

Topic 2.4 Ground water flow. Fully saturated analysis

Storage equation for fully saturated analysis. Groundflow velocities. To-tal, static and dynamic groundwater pressure. Groundflow permeability, expansion and capacity. Groundflow phreatic level. Static pressure height. Soil-water mixture bulk modulus. Reservoir Ground Flow Simulation in the Oil and Gas Industry. Ground Flow modelling in Computational Hydrology. Boundary conditions. Tochnog examples.

Topic 2.5 Non-saturated analysis

Permeability/pressure dependency diagram. Van-Genuchten model for nonsaturated ground water flow. Pore-pressure head. Saturated capacity. Boundary conditions. Tochnog examples.

Topic 2.6 Undrained groundflow analysis

Ggroundflow hydraulic head. Groundflow storage equation without permeability. Undrained capacity. Hydrostatic compressibility (average stress). Boundary conditions. Tochnog examples.

Topic 2.7 Convection and diffusion of heat

Convection-diffusion equation. Convection-diffusion temperature, density, capacity, conductivity, absorption and flow. Convection to environment. Radiation to environment.

Topic 2.8 Interaction analysis and advanced analysis in Tochnog

Fluid-structure interaction. Consolidation analysis. Ground water flow in deforming solid. Groundflow total pressure limit. Heat transport in ground water flow. Heat transport in materials. Boundary conditions. Tochnog examples.

TEACHING AND METHODOLOGICAL MAP OF THE DISCIPLINE

Full-time form of higher education with the use of distance learning technologies (DLT)

Title of section, topic	Title of section, topic	In-class hours					Independent work	Form of control
		Lectures	Practical classes	Seminar classes	Laboratory classes	Other		
1	2	3	4	5	6	7	8	9
1	**Finite element's mesh generation.**	**2**	**2**					
1.1	Computational geometry background.	2	2					interview test
2	**Computational mechanic and hydrodynamic.**	**16**	**16**					
2.1	Tochnog introduction.	2	2					interview test
2.2	Material deformation and flow.	2	2					interview test
2.3	Plasticity. Damage. Contact analysis.	2	2					interview test
2.4	Ground water flow. Fully saturated analysis.	2	2					interview test
2.5	Non-saturated analysis.	2	2					interview test
2.6	Undrained ground flow analysis	2	2					interview test
2.7	Convection and diffusion of heat	2	2					interview test
2.8	Interaction analysis and	2	2					interview

INFORMATION AND METHODOLOGICAL PART

List of basic literature

1. Bennett, A., Lagrangian Fluid Dynamics, Cambridge: Cambridge University Press, 2006. – 234 c.
2. Supercomputers and Their Performance in Computational Fluid Dynamics / ed. by Kozo Fujii. - Braunschweig : Vieweg, 1993. - 200 c.
3. Todd, D. K. and Larry, W. M. Groundwater Hydrology, third edition. John Wiley and Sons, Incorporated, 2004. - 656 c.

List of additional literature

4. Falkovich, H., Gregory, E. Fluid Mechanics (A short course for physicists), Cambridge University Press, 2011. – 357 c.
5. Dyke, P.P.G. An introduction to Laplace transforms and Fourier series. Springer, 1999. – 250 p.
6. Kantorovich, L.V., Krylov, V.I. Approximate methods of higher analysis. Interscience publishers, inc. 1958. – 681 c.
7. O'neil, P.V. Advanced engineering mathematics. 8th ed. Cengage Learning, 2017. – 1024 c.
8. Paz, M., Kim, Y.H. Structural dynamics. Theory and computation, 6th edition. – Springer, 2019. – 634 c.

List of recommended diagnostic tools and methodology for final mark formation

The main diagnostic tool is numerical FEM package TOCHNOG. Students should provide results of verification tests in text form and graphical presentations with help of science visualization ParaView.

The recommended diagnostic tools reveal the essential criteria for evaluating students' performance and correlate with the forms of knowledge control recorded in the teaching and methodological map.

The object of diagnostics of students' competences is the knowledge and skills acquired as a result of studying the academic discipline. Identification of students' learning achievements is carried out by means of current and interim certification.

The form of interim certification in the discipline "Computer Simulation in Problems of Underground Hydromechanics" in accordance with the curriculum is end-of-term test.

Approximate list of laboratory classes

1. Slope safety factor analysis. (2 h)
2. Non-saturated dam with seepage edge. (2 h)
3. Excavation with sheet pile, beam and contact spring elements. (2 h.)
4. Excavation with sheet pile and interface elements. (2 h.)
5. Confined compression of fluid filled porous material. (2 h.)
6. Plasticity in plate with circular hole. (2 h.)
7. Contact frictional heat generation. (2 h.)
8. Thermally induced stresses in plate. (2 h.)
9. Automatic local mesh refinement near shear band. (2 h.)

Description of innovative approaches and methods for teaching the discipline

When organizing the educational process, a heuristic approach is used, which entails the following:

- Students' personally significant discoveries of the surrounding world;
- Demonstration of solutions diversity to the majority of professional tasks and life challenges;
- Students' creative fulfilment in the process of designing educational products;
- Individualization of education through the opportunity to set goals independently and to reflect on one's own educational activity.

Methodological recommendations for the organization of independent work

For independent work in discipline "Computer Simulation in Problems of Underground Hydromechanics" the student can use following public resources. First of all the official side of Tochnog Professional - https://www.tochnogprofessional.nl/.

Tochnog Professional is a Finite Element program offering a wide variety of geotechnical and mechanical options; modern material laws including the most recent rate independent and viscous hypoplasticity models; stress, temperature and groundwater pressure analysis; lagrangian and eulerian mesh in space; quasi-static and dynamic calculations; a full libary of isoparametric elements in 1D, 2D and 3D and also featuring typical structural elements like beams, interfaces, springs, etc.; geometry based boundary conditions; mesh independent postprocessing by selecting physical points, lines and surfaces; 2D and 3D mesh refinement; phased modelling stages and extensive parallelisation.

The scope of geo filtration examples (https://tochnog.sourceforge.net/examples.html) includes: slope safety factor analysis; non-saturated dam with seepage edge modeling; excavation with sheet pile, beam and contact spring elements; excavation with sheet pile and interface elements; confined compression of fluid filled porous material; plasticity in plate with circular hole examples; contact frictional heat generation; thermally induced stresses in plate modeling; automatic local mesh refinement near shear band example.

The second sources of education materials is official side of CGAL Mesh Generation - https://doc.cgal.org/latest/Manual/packages.html#PartMeshing. The side contains a scope of practical methods like: mesh Generation; shape Reconstruction; geometry Processing. The side also include VS solutions examples and Python API.

Approximate list of questions for the end-of-term test

1. Basis of Finite element method.
2. Springs, trusses, beams and contact-springs elements.
3. Mesh generation. Algebraic methods. Differential equation methods. Elliptic schemes. Hyperbolic schemes.
4. Unstructured grid generation. The Delaunay Triangulation(DT). Ruppert's algorithm of DT
5. Line Segment Intersection. The planar graph. The Doubly-Connected Edge List.
6. Differential equation of material deformation and flow in Tochnog. Components of equation. Nearly incompressible Navier Stokes formulation. Linear solid formulation.
7. Elasticity, Elasto-Plasticity. CamClay plasticity model. Cap1 plasticity model.
8. Damage Mazars model.
9. Contact analysis. Contact with and without friction. Frictional heat generation. Penalty formulation.
10. Storage equation for fully saturated analysis. Groundflow velocities. Total, static and dynamic groundwater pressure. Groundflow permeability, expansion and capacity. Groundflow phreatic level. Static pressure height.
11. Reservoir Ground Flow Simulation in the Oil and Gas Industry.
12. Ground Flow modelling in Computational Hydrology.
13. Non-saturated analysis. Permeability/pressure dependency diagram
14. Van-Genuchten model for nonsaturated ground water flow..
15. Undrained groundflow analysis. Groundflow storage equation without permeability. Undrained capacity. Hydrostatic compressibility.
16. Convection and diffusion of heat. Convection-diffusion equation. Convection-diffusion temperature, density, capacity, conductivity, absorption and flow. Convection to environment.

ПРОТОКОЛ СОГЛАСОВАНИЯ УЧЕБНОЙ ПРОГРАММЫ УО

Название учебной дисциплины, с которой требуется согласование	Название кафедры	Предложения об изменениях в содержании учебной программы учреждения высшего образования по учебной дисциплине	Решение, принятое кафедрой, разработавшей учебную программу (с указанием даты и номера протокола)
Учебная дисциплина не требует согласования			

Заведующий кафедрой
д. ф.-м. н., профессор ____________ М.А. Журавков

28.05.2024

ДОПОЛНЕНИЯ И ИЗМЕНЕНИЯ К УЧЕБНОЙ ПРОГРАММЕ ПО ИЗУЧАЕМОЙ УЧЕБНОЙ ДИСЦИПЛИНЕ

на _____/_____ учебный год

№ п/п	Дополнения и изменения	Основание

Учебная программа пересмотрена и одобрена на заседании кафедры ______________________________(протокол № ____ от ________ 202_ г.)

(название кафедры)

Заведующий кафедрой

______________________ ________________

(ученая степень, ученое звание) (И.О.Фамилия)

УТВЕРЖДАЮ

Декан факультета

___________________ ________________

(ученая степень, ученое звание) (И.О.Фамилия)