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Research on Teaching Reform of Hydraulics Course Based on Numerical Simulation

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Abstract

Hydraulics is a core fundamental course for water resources–related majors, characterized by an abstract theoretical system and strong engineering applicability. To address the disconnection between theory and engineering practice in traditional teaching, this study proposes a reform plan that systematically integrates numerical simulation technology into the hydraulics curriculum. By constructing a "theory–simulation–application" integrated teaching model and using typical hydraulic structures as carriers, the reform reconstructs course content, innovates teaching methods, and optimizes the evaluation mechanism. The reform focuses on representative hydraulic structures such as gates, dams, weirs, and water conveyance systems, and designs hierarchical numerical simulation teaching cases. Through case-driven learning, project-based practice, and tiered instruction, students' engineering analysis abilities are effectively enhanced. This reform significantly improves students' understanding of complex flow phenomena, their proficiency in numerical tools, and their competence in solving engineering problems, providing a practical and operable pathway for curriculum reform in water resources engineering education.

Keywords

Hydraulics; Teaching reform; Numerical simulation; Hydraulic engineering; Teaching cases.

1. Introduction

Hydraulics is a core course for water resources-related majors, and its knowledge system directly supports the learning of subsequent specialized courses, such as hydraulic structures, hydropower stations, and water resources planning and management [1]. From dam spillway energy dissipation to pump station pipeline water conveyance, from river channel regulation to reservoir operation, nearly all aspects of water resources engineering design and operation rely on a profound understanding and application of hydraulic principles. However, the course's theoretical system is rigorous, involving partial differential equations and abstract concepts (such as boundary layer separation, water jump mechanisms, cavitation, etc.), making the traditional teaching model of "theory lectures + problem-solving exercises" insufficient for effectively linking abstract mathematical formulas with the complex and variable flow phenomena in water resources engineering. This disconnect directly leads to students having a vague understanding of the dynamic water load generation mechanism on hydraulic structures, superficial comprehension of the hydraulic design principles for energy dissipation and anti-scour in downstream spillway structures, and a lack of intuitive understanding of complex unsteady flow phenomena in pipeline and channel systems. As a result, the quality of talent cultivation in water resources engineering is severely constrained.

Numerical simulation technology, as the third scientific research paradigm following theoretical analysis and experimental research, provides new possibilities for addressing this teaching dilemma with its powerful flow visualization and parametric analysis capabilities. Through numerical simulation, large hydraulic structures can be "scaled down" to a computer screen, and transient flow processes can be "slowed down" with the ability to display physical quantities with color mapping, allowing students to gain deep insights into the underlying mechanisms [2]. This paper systematically explores how to use numerical simulation as a core teaching tool, to comprehensively reform the hydraulics curriculum, build a bridge connecting hydraulic theory with water resources engineering practice, and cultivate the next generation of engineers capable of using modern technical means to analyze and solve complex hydraulic problems in water resources engineering.

2. Existing Problems in Hydraulics Teaching

The teaching of hydraulics in water resources-related majors faces several prominent issues under the traditional model. These problems directly impact students' mastery of professional knowledge and the development of their engineering skills.

2.1. The Contradiction Between Complex Flow Phenomena and the Limitations of Teaching Methods

The flow phenomena studied in hydraulics are characterized by three-dimensional, unsteady, and complex features, involving intricate physical processes such as turbulence and cavitation. Traditional teaching relies on two-dimensional diagrams and simplified models, which struggle to accurately represent the complex characteristics of real flow phenomena, such as flood discharge from high dams and the rolling flow in energy dissipation pools. These limitations in representation make it difficult for students to establish an accurate spatial concept of flow, leading to a superficial understanding of core concepts like boundary layer development and vortex structures.

Numerical simulation technology enables three-dimensional dynamic visualization of the flow field, transforming abstract flow parameters into intuitive images. However, the limitations of traditional teaching methods prevent this advantage from being fully utilized. Although students learn theoretical formulas, they often find it challenging to establish a direct connection between mathematical expressions and real flow phenomena. This cognitive barrier directly impacts the depth of their understanding of the nature of fluid motion.

2.2. Disconnection Between the Knowledge System and Engineering Applications

Traditional courses organize knowledge points by chapters and train students through isolated exercises, which can easily lead to a fragmented understanding of the subject. Real-world engineering problems, such as the design of flood discharge structures, require the integrated application of multiple knowledge areas, including hydrostatics, energy equations, and more, for systematic analysis. This ability to perform comprehensive analysis is a core competence for engineers, yet the traditional teaching model struggles to cultivate it effectively.

Numerical simulation provides a systematic analysis platform for complex engineering problems. In a virtual environment, students can observe the interactions among different physical processes and analyze the coupling relationships between various parameters. This systematic cognitive experience helps students build a complete knowledge network, compensating for the lack of knowledge integration in traditional teaching.

2.3. Disconnection Between Teaching Content and Industry Development

Numerical simulation technology has become an important tool in the field of water resources engineering, widely applied in engineering design, safety evaluation, and other aspects. However, university-level hydraulics teaching still focuses primarily on analytical derivations and manual calculations, creating a noticeable gap between academic instruction and industry technological development [3]. This lag directly affects students' employability and their potential for professional growth.

Introducing numerical simulation into teaching is a key measure to align course content with industry practices. By engaging with and using modern technological tools, students can adapt to industry workflows in advance and develop the ability to apply advanced techniques to solve engineering problems. Such teaching reform has a positive impact on improving the quality of talent cultivation.

3. Overall Design of Teaching Reform Based on Numerical Simulation

3.1. Reform Philosophy and Objectives

This teaching reform adheres to the core philosophy of "engineering problem-oriented, using numerical simulation as a tool to promote the coordinated development of theoretical knowledge and engineering skills." This philosophy is based on a thorough analysis of the current needs for cultivating modern water resources engineering talent. It aims to break down the barriers between theory and engineering practice through innovative teaching methods. The reform not only focuses on knowledge transmission but also emphasizes the development of students' ability to analyze and solve complex engineering problems using modern technical tools. This ensures that students can master basic theoretical knowledge while becoming proficient in using numerical simulation tools for engineering practice, thus facilitating the effective transformation from theoretical knowledge to engineering application skills.

Based on this philosophy, the reform establishes a systematic teaching objective that encompasses three dimensions: knowledge, ability, and quality [4]. In terms of knowledge, a numerical simulation case library for typical hydraulic flows is constructed, allowing students to intuitively understand the engineering background and physical essence of core concepts such as dynamic water load distribution, cavitation mechanisms, and energy dissipation principles. In terms of ability, the focus is on cultivating students' practical skills in building computational models, setting boundary conditions, and analyzing simulation results, thus enhancing their comprehensive ability to perform hydraulic analysis and optimization of engineering solutions using hydraulic theory. In terms of quality, the reform emphasizes developing students' rigorous scientific attitude, professional awareness of engineering safety, and innovative thinking in solving complex hydraulic problems using modern technology. These three dimensions support and complement each other, forming a complete teaching objective system.

3.2. Positioning and Selection of Numerical Simulation Tools

In terms of teaching positioning, numerical simulation tools are explicitly regarded as important auxiliary means for hydraulic analysis of hydraulic structures. The teaching emphasis lies in cultivating students' ability to abstract real engineering problems into mathematical models and to reasonably interpret and analyze computational results. This positioning reflects the fundamental principle of “tools serving teaching,” emphasizing that numerical simulation practice helps students develop systematic engineering analysis thinking and master the complete workflow from problem identification and model construction to result evaluation. At the same time, it focuses on fostering students' critical thinking regarding computational results, enabling them to accurately assess the reliability of simulations and understand the applicability and limitations of different models.

Regarding software selection, a multi-level and complementary teaching tool system is constructed based on the characteristics and development needs of the water resources engineering discipline. On one hand, general-purpose CFD software such as ANSYS Fluent/CFX is selected to leverage its powerful flow field analysis capabilities, helping students gain a deep understanding of the physical mechanisms of complex flow phenomena [5]. On the other hand, MIKE series software, specialized for water resources engineering, is introduced to take full advantage of its professional capabilities in river flow simulation, flood propagation analysis, and hydraulic calculation of water structures. By integrating these two types of software in a complementary manner, the approach ensures that students gain a solid understanding of fundamental flow mechanisms while enhancing their ability to solve real engineering problems, allowing them to select and apply appropriate analytical tools and methods according to the specific characteristics of each problem.

4. Implementation Path of Teaching Reform

4.1. Reconstruction and Integration of Teaching Content

Based on the characteristics of water resources-related majors, a three-level teaching content system has been established, comprising fundamental theory, professional application, and engineering innovation. By systematically integrating numerical simulation content, a teaching structure has been formed that deeply combines theoretical instruction with engineering practice. The specific design of numerical simulation teaching topics is presented in Table 1 [6].

Table 1. Design of numerical simulation teaching topics in hydraulics

Topic category	Core knowledge points	Simulation cases
Water-retaining Structures	Hydrostatic pressure, Seepage theory	Gravity dam uplift pressure analysis, Embankment dam seepage field simulation
Flood discharge structures	Orifice flow, Energy equation, Hydraulic jump theory	Spillway discharge coefficient analysis, Energy dissipation pool hydraulic characteristics simulation
Water conveyance structures	Pipe flow resistance, Open channel flow	Pump station pipeline system analysis, Trapezoidal channel hydraulic calculation
Other hydraulic structures	Boundary layer theory, Flow-around resistance	Local scour simulation around bridge piers, Hydraulic characteristics analysis of culverts

At the fundamental theory level, while maintaining the integrity of the core knowledge system of hydraulics, the focus is placed on strengthening its relevance to water resources engineering practice. By introducing fundamental numerical experiments such as gravity dam uplift pressure analysis and embankment dam seepage field simulation, students are able to intuitively understand the application value of these theories in engineering practice when learning basic concepts such as hydrostatic pressure and seepage theory. For example, when explaining the distribution of hydrostatic pressure, students are required to use numerical simulation to verify the principle that "pressure is proportional to water depth" and calculate the total pressure acting on the dam face, closely linking abstract concepts with specific engineering problems.

At the professional application level, the four topics designed in Table 1 systematically cover the major types of hydraulic structures in water resources engineering. The water-retaining structures topic helps students understand the stress characteristics of different types of dams through examples of gravity dams and embankment dams. The flood discharge structures topic, through actual engineering cases of spillways and energy dissipation pools, provides in-depth analysis of discharge capacity and energy dissipation mechanisms. The water conveyance structures topic focuses on pump station pipeline systems and irrigation channels, studying the hydraulic characteristics of pressurized pipelines and open channels. The other hydraulic structures topic explores local hydraulic phenomena and protective measures for common water structures, such as bridge piers and culverts.

At the engineering innovation level, comprehensive design projects, such as "Overall hydraulic system analysis of a reservoir hub," are set up, requiring students to integrate knowledge and skills from multiple topics to complete the entire process, from identifying engineering problems and constructing numerical models to calculation analysis and solution optimization. Through this systematic training, students develop engineering thinking and innovation capabilities, laying a solid foundation for future careers in water resources engineering design and management.

4.2. Innovation in Teaching Methods

In terms of teaching methods, this reform constructs a diversified teaching method system, combining case-driven teaching, project-based learning, and tiered teaching. These three methods complement each other and progress step by step, comprehensively improving teaching effectiveness. Together, they facilitate the mastery of theoretical knowledge, the development of practical skills, and the cultivation of innovative thinking in students.

Case-driven teaching uses typical water resources engineering problems as case studies. Through the teaching path of "theoretical guidance – simulation verification – engineering application," it cultivates students' engineering thinking abilities. In the water-retaining structures section, a gravity dam is used as a specific case. Students are guided to first analyze the dam's stress through theoretical calculations, then build a numerical model to verify the results, and finally discuss the effect of uplift pressure on dam stability in the context of engineering practice. In the flood discharge structures section, the hydraulic design of energy dissipation pools is used as an example. Students use numerical simulation to observe the changes in flow patterns at different Froude numbers, intuitively understanding the energy dissipation mechanism, and further optimizing the energy dissipation pool design. This teaching method, based on real engineering cases, effectively bridges the gap between theory and practice, deepening students' understanding of knowledge through the process of solving specific problems.

Project-based learning focuses on cultivating students' engineering practice abilities and teamwork skills by setting up complete project tasks that simulate real engineering workflows. During project implementation, students work in groups of 4-6 to complete projects with practical backgrounds, such as "Hydraulic Calculation and Optimization of a Canal System" or "River Channel Rehabilitation Flow Simulation and Scheme Comparison." Each group goes through stages including field research, data collection, scheme design, numerical simulation, result analysis, and report writing, with the final project presented in a defense session. For example, in the canal system hydraulic calculation project, students are required to layout the canal system based on actual topographic conditions, use numerical simulation to calculate the water surface profile for each section, and optimize the channel slope and cross-sectional form based on the results. This learning experience, based on the complete workflow, not only cultivates students' professional technical skills but also develops their project management, teamwork, and communication abilities.

Tiered teaching is designed to address individual student differences and implement differentiated training strategies [7]. Through entrance tests and early performance evaluations, students are divided into three levels: basic, intermediate, and advanced. Personalized teaching objectives and methods are then developed for each level. For students at the basic level, detailed step-by-step guidance and template files are used to focus on developing their software operation and basic simulation skills, ensuring they master core competencies. For intermediate-level students, more challenging tasks, such as simulating flow under complex boundary conditions, are set to cultivate their independent analytical and problem-solving abilities. For advanced-level students, participation in faculty research projects or the independent design of innovative experiments is encouraged, such as the development of new energy dissipation structures or research on the stress characteristics of structures under complex flow conditions, to cultivate their research and innovation capabilities. This tiered, progressive teaching approach ensures that all students meet the basic educational requirements while providing opportunities for outstanding students to excel, achieving the goal of personalized education.

4.3. Teaching Evaluation

To scientifically assess students' learning outcomes in numerical simulation teaching, this reform incorporates numerical simulation competence into the overall course evaluation system, assigning it a weight of 10% of the total grade. The assessment focuses on the core competencies of numerical simulation, aiming to comprehensively reflect students' proficiency in modeling, analysis, and innovative application [8].

The 10% of the total grade is specifically allocated as follows: Modeling ability (3%) is assessed through in-class exercises and homework assignments, focusing on students' ability to construct numerical models for hydraulic engineering, including the accuracy of geometric modeling, the quality of grid generation, and the reasonableness of parameter settings as fundamental skills. Analysis ability (4%) is evaluated through simulation lab reports, emphasizing students' ability to interpret calculation results, integrate theoretical knowledge, and apply hydraulic principles to analyze engineering problems in depth. Innovative application ability (3%) is based on students' performance in comprehensive projects, focusing on evaluating their innovative thinking and practical ability to solve complex engineering problems using numerical simulation methods.

This assessment design reflects a comprehensive coverage of all aspects of numerical simulation teaching. It not only emphasizes the development of basic modeling skills but also highlights the enhancement of analysis capabilities and innovative thinking. Through such an allocation, the evaluation can objectively reflect students' proficiency in applying numerical simulation and effectively guide them to focus on the overall development of numerical simulation skills, ensuring the effective achievement of teaching goals.

5. Teaching Effectiveness Analysis

5.1. Deepening Knowledge Understanding

Through the visualized teaching of numerical simulations, students are able to gain a deeper understanding of abstract hydraulics concepts. In the study of spillway dams, flow display technology transforms abstract parameters such as pressure distribution on the dam face and velocity variations into intuitive images, helping students establish a direct connection between theoretical knowledge and engineering phenomena. This teaching method enables students to accurately grasp the essential characteristics of complex flow phenomena, integrating mathematical expressions in textbooks with actual physical processes. Particularly in the analysis of cavitation phenomena, the visualized pressure contour maps allow students to clearly understand the relationship between negative pressure zones and cavitation risks, effectively promoting a deeper mastery of professional knowledge.

5.2. Enhancing Practical Abilities

Systematic numerical simulation training has effectively enhanced students' engineering practice abilities. In topics such as downstream flow from gates and energy dissipation pools, students use parametric analysis to understand the flow characteristics under different operating conditions, developing their ability to comprehensively analyze engineering problems. This training, based on real engineering contexts, allows students to proficiently use professional software for hydraulic calculations of water engineering structures, laying a solid foundation for future engineering practice. Graduation project results show that students can independently apply numerical simulation methods for design and optimization, demonstrating strong engineering application abilities.

5.3. Cultivating Innovative Thinking

The implementation of project-based learning has promoted the development of students' systematic thinking and innovation abilities. In comprehensive projects such as irrigation system hydraulic analysis, students need to consider all aspects of the engineering system and analyze problems from a holistic perspective. This training approach allows students to break through the limitations of isolated knowledge points in traditional teaching, establishing a systematic engineering thinking model. By solving complex engineering problems, students are able to consider multiple factors such as technical feasibility, safety, and economic viability, proposing innovative solutions that showcase excellent engineering qualities and development potential.

6. Conclusions

This study systematically establishes a hydraulics course teaching reform system driven by numerical simulation. By deeply integrating numerical simulation techniques with the analysis of typical hydraulic structures, a novel teaching model has been formed that seamlessly connects theoretical instruction with engineering practice. The reform adopts case-driven teaching, project-based learning, and tiered instruction as its core methods, constructing a hierarchical teaching case library centered on typical hydraulic structures, thereby achieving comprehensive training from fundamental theory to engineering application. Practical results indicate that this approach significantly enhances students’ understanding of complex flow phenomena, numerical modeling and analysis abilities, as well as problem-solving skills in engineering, effectively facilitating their transformation from knowledge recipients to innovative practitioners.

This study provides a complete implementation pathway and innovative paradigm for hydraulics course reform. It offers a systematic solution in terms of teaching content reconstruction, instructional method innovation, and evaluation mechanism optimization. This model not only strengthens students’ engineering literacy and practical abilities but also promotes effective alignment between course content and industry development. In the future, efforts will continue to improve the construction of the teaching case library, deepen the application of integrated virtual-physical teaching platforms, and expand the role of numerical simulation throughout the curriculum, providing sustained support for the cultivation of water resources professionals in the new era.

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