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Application of AI and Digital Twin Technology in Practical Teaching of Geological Hazard Courses: Taking Earthquake Disaster as an Example

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Abstract: In response to the three major contradictions, safety, cognition, and ability cultivation, existing in the practical teaching of geological hazard courses, this paper proposes a "virtual-real integration" teaching reform scheme, using earthquake disasters as an example. By integrating digital twin technology and artificial intelligence technology, a four-layer teaching framework consisting of data layer, model layer, platform layer, and intelligent layer is constructed. Progressive teaching segments of "cognition-simulation-decision-making" are designed to establish a comprehensive training path from seismic geological survey to disaster early warning and decision-making. This scheme shifts the traditional field practice venue to a safe virtual environment, promotes students' understanding of geological hazards from static fragments to dynamic processes, enhances their comprehensive decision-making ability in geological disaster prevention and mitigation, and provides theoretical support and practical guidance for cultivating interdisciplinary talents in geological hazard prevention.

Keywords: Virtual-real integration; Digital twin; Artificial intelligence; Practical teaching; Earthquake disaster

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1. Introduction

China features diverse types of geological hazards, widespread distribution, and poses severe threats. Cultivating talents in geological disaster prevention with solid theoretical foundations, excellent practical abilities, and cutting-edge technological literacy is an urgent need to serve the national public security strategy [1]. Among these, earthquake disasters, as a typical type of geological hazard, hold significant representative meaning for teaching [2].

Currently, higher education in China is deeply advancing the "New Engineering" construction [3] and the

"Educational Digitalization" strategic action [4], explicitly proposing to promote the deep integration of new-generation information technologies such as artificial intelligence and big data with education and teaching, to solve teaching challenges and innovate talent cultivation models. Digital technology, as a core force driving systemic change in education, is leading the global restructuring of educational paradigms [5]. In this context, Artificial Intelligence (AI) and Digital Twin technologies provide revolutionary tools for the reform of practical teaching in geological hazard courses [6]. AI technology, with its powerful perception, analysis, and prediction capabilities, can deeply mine hidden patterns within massive geological hazard monitoring data; while Digital Twin technology can construct high-fidelity models and dynamic simulations, building a "geological hazard teaching scene" parallel to the physical world in virtual space, achieving precise mapping and scenario reproduction of real disaster processes [7].

The combination of the two offers a new path to break through the spatiotemporal limitations and safety bottlenecks of traditional practical teaching in geological hazard courses. However, the traditional practical teaching model faces significant contradictions in terms of safety, cognitive depth, and ability cultivation, which have become key bottlenecks restricting the improvement of teaching effectiveness [8]. By constructing an intelligent, practical teaching system featuring "virtual-real integration," students can "experience" the entire process from disaster incubation, occurrence, and development to emergency response in a safe, controllable, and repeatable virtual environment [9]. This deeply cultivates their abilities in disaster data analysis, early warning algorithm application, and comprehensive decision-making. This paper takes earthquake disasters as an example to analyze the dilemmas of traditional practical teaching in geological hazard courses and explore new talent cultivation paths empowered by AI and Digital Twin technologies.

2. Realistic dilemmas of traditional practical teaching

2.1. Contradiction between teaching safety and practical depth

Typical earthquake fault zones, extreme disaster areas post-earthquake, and other field sites are often located in remote areas with complex environments and inherent high risks. Organizing large-scale student field internships poses significant safety hazards [10]. This often leads to teaching being primarily based on "distant observation and explanation," making it difficult for students to conduct close-range, refined observation and operation, thereby limiting practical depth and the cultivation of hands-on ability.

2.2. Contradiction between cognitive comprehensiveness and process staticity

Earthquake disaster is a complete dynamic process encompassing incubation, occurrence, development, and disaster formation, with a time span potentially reaching millennia and a vast spatial influence range. However, traditional field internships can only observe the "static results" after prolonged geological processes. Students cannot intuitively perceive dynamic processes such as rupture propagation, wavefield changes, and disaster chain evolution, leading to an understanding of earthquake mechanisms remaining at an abstract level and making it difficult to establish systematic and process-oriented cognition.

2.3. Contradiction between ability comprehensiveness and training singularity

The core competitiveness of talents in earthquake disaster prevention lies in their comprehensive decision-making and emergency response capabilities under complex scenarios, which need to be cultivated through repeated "decision-execution-feedback" training. However, the irreversible nature of real earthquake disasters and the high time and economic costs of field internships make such high-intensity training difficult to conduct.

Students lack opportunities for trial and error and practice in comparing and optimizing multiple solutions, which restricts the enhancement of their innovative thinking and practical problem-solving abilities.

3. Advantages of AI and digital twin technology in the practical teaching of geological hazard courses

3.1. Fundamentally enhancing teaching safety

Traditional field internships often face high-risk environments such as active fault zones and post-earthquake danger zones, severely restricting the in-depth development of practical teaching. Digital Twin technology constructs precise digital mirrors of high-risk scenes, allowing students to safely perform operations like deep fault zone investigation and seismic damage survey in a virtual environment, completely eliminating personal safety risks.

3.2. Revolutionizing the optimization of teaching process and cognitive experience

Earthquake processes that are difficult to present in traditional teaching are realized through AI-driven dynamic simulation, achieving a cognitive leap from abstract to concrete. The Digital Twin platform can visually reproduce processes spanning vast spatiotemporal scales, such as earthquake incubation, wave propagation, and disaster chain evolution, enabling students to intuitively perceive dynamic earthquake processes. Research indicates that Digital Twin technology, by constructing high-fidelity virtual scenarios, can intuitively and repeatably present abstract and irreversible natural processes to students, fundamentally revolutionizing the learners' cognitive experience [11].

3.3. Realizing scalable, personalized, and comprehensive ability cultivation

In teaching scenarios like "Earthquake Disaster Chain Deduction," AI dynamically adjusts disaster scenarios based on students' decision-making processes, providing targeted ability training. Meanwhile, the platform supports multi-person online collaboration, allowing students to cultivate teamwork and comprehensive decision-making abilities in complex earthquake disaster scenarios.

4. Core concept and systemic theoretical framework construction

The core connotation of the "virtual-real integration" practical teaching concept (**Figure 1**) advocated in this paper is: using real-world earthquake disaster scenarios as the blueprint, utilizing Digital Twin technology to construct their high-fidelity, computable virtual entities, and embedding AI as the core for dynamic driving and intelligent interaction, thus forming a "earthquake disaster practice metaverse" parallel, interactive, and co-evolving with the physical world. This concept draws upon cutting-edge interdisciplinary research paradigms, as emphasized by Bibri *et al.* [12], the synergistic effects of artificial intelligence and digital twins enable deep perception, dynamic simulation, and intelligent decision-making for complex systems. In this environment, students can engage in full-chain, immersive learning from macro exploration, process inversion to emergency decision-making, achieving substitution, enhancement, and deepening of the high-risk, large-scale, irreversible earthquake disaster processes.

4.1. Data layer

Establish a multi-source heterogeneous data fusion system, integrating multi-dimensional professional data such as seismic network waveform data, GNSS monitoring data, InSAR deformation data, active fault survey data, and seismic damage case libraries. Adopt unified data standards and metadata management specifications, construct a distributed data storage architecture, and realize real-time access, quality control, and dynamic updating of seismic data.

4.2. Model layer

Construct a multi-dimensional model system, containing three major technical modules: geometric modeling of earthquake scenes based on BIM+GIS for high-precision modeling of active faults and seismogenic structures; integration of physical mechanism models such as finite element solution of seismic wave equations and fault rupture dynamics simulation; deployment of professional AI models such as U-Net for active fault identification, CNN for seismic phase detection, and LSTM for earthquake prediction.

4.3. Platform layer

Construct a dedicated earthquake disaster teaching platform based on Unity/Unreal Engine, adopting a microservices architecture design, including core modules such as earthquake scene management, wavefield rendering, physics engine, and network communication. The platform supports multi-terminal access, provides rich earthquake-specific development interfaces and visual editing tools, and possesses high-concurrency processing capability and cross-platform deployment characteristics.

4.4. Intelligent layer

Construct an intelligent teaching engine, containing three core modules: seismic perception and recognition, disaster deduction and simulation, and teaching evaluation and feedback. The perception and recognition module integrates various seismic professional algorithms to achieve automatic extraction and labeling of elements such as active faults and seismic damage characteristics; the deduction and simulation module integrates physical models and data-driven methods to support real-time simulation of complex earthquake processes; the evaluation and feedback module, based on multi-objective optimization algorithms, provides quantitative evaluation and intelligent guidance for the operation process.

5. Core instructional design and implementation pathway

Based on the constructed theoretical framework, this paper designs three progressive instructional stages, closely aligned with the characteristics of Geological Disaster Courses, to build a comprehensive competency development system. Each stage follows the pedagogical logic of "from cognition to practice, from analysis to decision-making," systematically enhancing professional literacy and technical skills through immersive digital experiences.

5.1. Cognition stage

This stage focuses on cultivating spatial cognition and geological analysis capabilities. Students utilize the Digital Twin platform, employing multi-source remote sensing data and AI recognition algorithms to conduct intelligent identification and interpretation of active faults. Through models such as U-Net, automatic extraction of fault structures is achieved, and results are spatially validated using 3D analysis tools. This process strengthens the application of students' professional knowledge and establishes a systematic cognitive framework from macro to micro scales.

5.2. Simulation stage

This stage emphasizes the training of engineering simulation and data analysis skills. Within the virtual seismic motion field environment, students utilize physical mechanism models and AI early-warning algorithms to conduct real-time simulation of wave propagation processes and early-warning analysis. By configuring source parameters, observing wavefield characteristics, and employing CNN models for phase identification and parameter calculation, students deepen their theoretical understanding and master core early-warning technologies under the guidance of real-time feedback from the intelligence layer.

5.3. Decision-making stage

This stage aims to develop students' systems thinking and emergency decision-making abilities. Based on Digital Twin urban disaster scenarios, students complete comprehensive training spanning from disaster identification to emergency decision-making. Through dynamic simulation of disaster chain development by the intelligence layer, students analyze real-time disaster information and formulate response strategies, engaging in team collaboration via the platform's cooperative functions. The evaluation system quantitatively assesses decision-making effectiveness across multiple dimensions, comprehensively enhancing students' overall competency in addressing complex engineering problems.

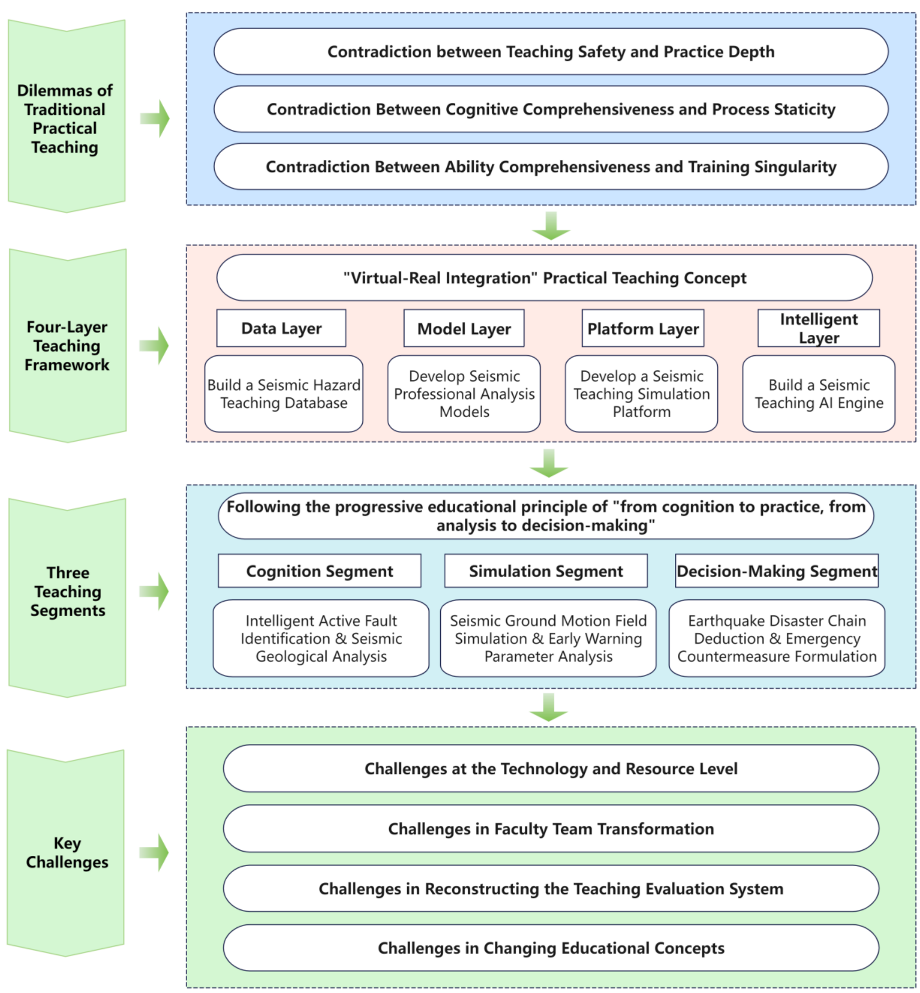

Figure 1. Schematic diagram of the "virtual-real integration" teaching framework

6. Key challenges

6.1. Challenges at the technology and resource levels

The construction cost of high-fidelity Digital Twin platforms is high, and the simulation of earthquake processes requires stringent algorithm accuracy. It is recommended to adopt a phased construction strategy, prioritizing the development of core teaching modules; establish school-enterprise resource sharing mechanisms; and implement model accuracy grading schemes to balance teaching needs and computational efficiency.

6.2. Challenges in faculty team transformation

The existing teaching staff generally lacks an interdisciplinary background in seismology and information science. A "dual-qualified" teacher development mechanism should be established, promoting knowledge updating through school-enterprise jointly built workstations [13]; develop innovative talent recruitment mechanisms to attract young teachers with interdisciplinary backgrounds.

6.3. Challenges in reconstructing the teaching evaluation system

Traditional evaluation methods are inadequate for assessing higher-order abilities such as innovative thinking. It is recommended to construct a "digital portfolio" system that records decision-making processes in the virtual environment throughout the course, combined with AI analysis technology to achieve precise evaluation of ability development.

6.4. Challenges in changing educational concepts

In response to some educators' skepticism about the effectiveness of virtual practice, it is necessary to clarify the reform positioning of "virtual-real combination, complementary advantages." Indeed, intelligent technologies are driving the digital transformation of the entire educational paradigm [14]. Furthermore, explorations of AI-empowered teaching reform in related fields such as geological engineering have also demonstrated great potential [15]. By developing typical teaching demonstration lessons, systematically demonstrate the unique value of Digital Twin technology in presenting earthquake teaching processes and simulating risks, and establish an organic connection mechanism between virtual practice and field internships.

7. Conclusion

This paper innovatively proposes a "virtual-real integration" teaching concept centered on Digital Twin and Artificial Intelligence technologies, and systematically constructs a professional four-layer teaching framework. This paradigm successfully "brings" high-risk, irreversible seismic and geological disaster processes into the classroom by creating a high-fidelity, dynamically evolving virtual practice environment, achieving a systematic upgrade of the traditional practical teaching model for geological hazard courses.

Focusing on the professional needs of geological hazard courses, this paper designs three teaching segments of "cognition-simulation-decision-making," forming a complete ability cultivation chain from seismic geological foundations to disaster emergency decision-making. This system effectively resolves the three core contradictions in traditional teaching and systematically cultivates professional and practical abilities and scientific decision-making abilities.

The teaching framework and implementation strategies proposed in this paper are closely integrated with the professional characteristics of geological hazard courses, including professional content such as the processing and application of seismic data, construction methods of seismic damage scenarios, and practical training of early warning algorithms. It provides a complete reference for similar institutions to carry out practical teaching reforms for geological hazard courses, promoting the deep integration of new-generation information technology with geological hazard course education.

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Disclosure statement

The authors declare no conflict of interest.

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