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Review of The Research Status of Numerical Simulation of Dike Pipe Surge

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Abstract

Dike pipe surge is a threatening water conservancy engineering disaster which refers to a large amount of groundwater flow phenomenon inside the dike due to the concealment of pipe surge. This lack of in-depth study of the pipe surge mechanism seriously affects the safety of people's lives and property. In recent years, with the development of science and technology, numerical simulation technology has been widely used in water conservancy projects, allowing for more accurate simulation and prediction of dikes and foundation pipe surges. By organizing the current research status at home and abroad, this paper summarizes the research status of pipe surge from three directions: numerical simulation research of pipe surge, factors affecting pipe surge research, and visualization research of pipe surge occurrence mechanism. Based on this, the future development trend of numerical simulation research on dike pipe surge is predicted.

Keywords

Dam Foundation; Pipe Surge; Numerical Simulation; Discrete Elements.

1. Introduction

China has numerous reservoirs and dams. Over the years of operation, under the influence of internal and external environments, they face many safety issues, mainly manifesting as long-term seepage, piping, percolation, soil flow in earth-rock dams, and even swamp formation at the dam foot[1]. Piping can be divided into body piping and foundation piping.

Foundation piping, a phenomenon of large underground water flow within the dam foundation, easily causes soil instability and dam failure, posing a threat to the safety and stability of water conservancy projects. Traditional experimental methods are limited by time, location, cost, etc., making it difficult to simulate actual conditions. However, numerical simulation technology can predict the location, range, and flow of piping in a short time, providing scientific basis for the prevention and control of piping, reducing engineering safety risks, and having significant practical application value.

Moreover, predicting the occurrence and evolution of piping through numerical simulation can provide more accurate basic data for engineering design and improve the seismic and sliding resistance of the project. Therefore, numerical simulation research on foundation piping has high theoretical and practical value.

2. Research Status

2.1. Mechanism of Piping

Piping in dam foundations refers to the phenomenon of large underground water flow due to the presence of a non-water-bearing layer above the aquifer, with sufficient water pressure difference between the two, causing water to continuously infiltrate downwards from the upper aquifer, forming foundation piping[2]. The mechanism of piping is mainly related to the following situations:

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(1) Natural disasters such as mudslides or flash floods cause the water level in the aquifer to rise, exceeding the saturation pressure of the non-water-bearing layer.

(2) Sudden increases in rainfall or pressure around the dam lead to water pressure exceeding the saturation pressure of the non-water-bearing layer.

(3) Groundwater extraction activities around the dam cause a decrease in water pressure in the non-water-bearing layer.

In these situations, water from the aquifer enters the non-water-bearing layer through cracks and pores, accumulating below it and forming pressure, causing water to backflow and seep out from the underlying aquifer, resulting in foundation piping. Understanding the mechanism of piping is crucial for its prevention and control.

2.2. Domestic Research Status

In the early stages, due to technological limitations, researchers often used continuum-based methods to simulate piping. Zhu Wei[3] analyzed and discussed the mechanism of foundation seepage failure and its influencing factors using finite element saturated-unsaturated seepage analysis, addressing issues encountered in the Abukuma River foundation seepage prevention project in Japan. Even today, this method and its improvements still hold a significant place in piping research. Xu Youyuan[4] used the large general finite element analysis software ANSYS to analyze the seepage field issues of piping and briefly discussed the direction for further work. Liu Changjun[5] employed the mesh-free Galerkin method to study the dynamic development process and mechanism of piping erosion in dam foundations.

The essence of piping is the migration of particles through pore channels. The discrete element method (DEM), originating from molecular dynamics, uses discrete particles as its basic research units. It is evident that applying this method to piping simulation analysis is more targeted. Consequently, more scholars are attempting to use DEM to study the mechanism of piping, achieving many positive results.

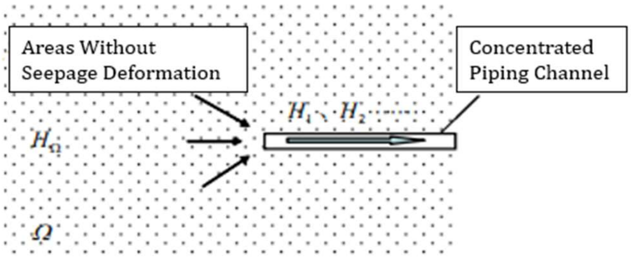

Figure 1. Schematic diagram of head coupling calculation of pipe surge channel

Jiang Mingjing[6] used the discrete element method (DEM) to perform numerical simulations of piping phenomena. To verify the fluid-particle coupling calculation function, they first used DEM to analyze stable seepage (Figure 1 shows the schematic diagram of the head coupling calculation in the piping channel), obtaining results that conformed to Darcy's law. They analyzed the quicksand phenomenon and obtained results close to the theoretical critical hydraulic gradient, then analyzed the piping phenomenon with simple grading. Zhou Xiaojie[7] employed the element-free Galerkin (EFG) method to adapt to the continuously changing internal boundary conditions during calculations. Case calculations demonstrated that this seepage-pipe flow coupling method could simulate the complex development process of piping channels bypassing impermeable walls. Subsequently, Ren He[8] applied the natural element method (NEM) to simulate the development process of piping, replacing the previous EFG method. Compared to the EFG method, the shape functions of the NEM satisfy the Kronecker delta condition, allowing for more accurate application of boundary conditions.

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Wu Mengxi[9] addressed the binary dam foundation piping problem, where the surface layer is a relatively impermeable clayey thin layer and the lower layer is a sandy layer. They proposed a finite element numerical model for simulating flow soil-type piping that develops retrogressively in the form of a pipeline within the dam foundation. The model considered the effect of sand concentration in the piping channel on water flow resistance and was able to quantitatively simulate the dynamic development process of piping over time.

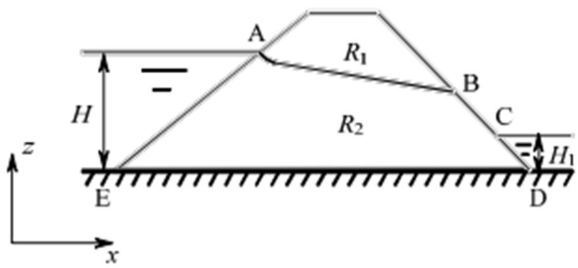

Figure 2. Schematic diagram of the boundary of the stable seepage dam

Hu Yayuan[10] conducted a finite element numerical analysis of the seepage erosion problem in a two-dimensional homogeneous earth-rock dam with a free surface, using the modified SPV piping control equation, the Newton-Raphson method, and the transfer matrix adjustment method. The analysis showed that piping erosion increases the permeability coefficient of the dam, significantly affecting the seepage velocity of the dam but having a smaller impact on the pore pressure distribution and the position of the free surface.

Li Xiaoqing[11] studied the influence of different gradation characteristics of piping soils (continuous gradation and gap gradation) on the piping mechanism. Based on particle flow theory and fluid-solid coupling effects, they used the FISH programming language embedded in the PFC3D program to establish a seepage model of the foundation-filter system. They conducted a series of numerical simulation experiments under different interlayer coefficients. The results indicated that when the interlayer coefficient values of the foundation-filter system are within an optimal range, the soil exhibits good soil-retention and water-permeability properties, and the continuous gradation characteristic of the foundation soil has a strong self-filtration capability.

Table 1. Physical parameters of embankment soil

Soil	D_{60}/mm	D_{30}/mm	Dry density/($g \cdot cm^{-3}$)	Particle density/ ($g \cdot cm^{-3}$)	n	Permeability coefficient/ ($m \cdot s^{-1}$)
Gravel	4.10	0.85	1.80	2.65	0.32	8.7×10^{-4}
Fine Sand	0.18	0.14	1.39	2.68	0.48	3.7×10^{-5}

Wang Shuang[12] simulated the dynamic development process of piping in multi-layer dam foundation structures using finite element analysis software. They analyzed the distribution of the seepage field within the dam foundation at different stages of piping development. By comparing the hydraulic gradients of various regions with the critical hydraulic gradients for soil erosion in those regions, they determined the areas and ranges of particle loss at each stage of piping development.

2.3. Foreign Research Status

Compared to domestic research, the progress and development routes of numerical simulation studies on piping abroad have many similarities to those in China. Kenichi[13] used the discrete element method (DEM) to conduct internal piping research. Their analysis indicated that for samples with different grain size distribution (GSD) curves, the loss of fine particles led to changes in the microstructure of the particle chain network, even if the boundary stress state remained constant.

To finely simulate the seepage field during the piping process, Sibille Luc[14] used a fully coupled discrete element-lattice Boltzmann method (DEM-LBM) to analyze seepage and piping erosion. The discrete element method was used to describe the interactions between solid particles, while the lattice Boltzmann method was employed to solve the water dynamics problem. The results of the numerical simulation indicated that the internal erosion of the solid phase could be described by hydraulic shear stress or the energy consumed by seepage.

Mandie S. Fleshman[15] conducted indoor model tests to evaluate the mechanism of piping erosion in sandy soils under different gradations, grain sizes, particle shapes, and specific gravities. They observed and monitored the testing process, correlating the observed behavior with the measured pore pressure states in the samples. Based on this, they established a mechanical model for the development of piping.

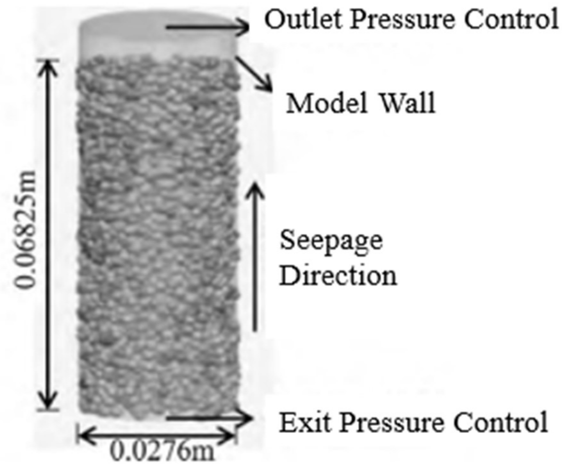

Figure 3. CFD-DEM model diagram

Junliang Tao, Ph.D.[16] used coupled computational fluid dynamics (CFD) and discrete element method (DEM) to re-study the effects of specific gravity, initial porosity, particle size distribution (PSD), aspect ratio of sand samples, and friction coefficient on piping resistance (Figure 3 shows the model established using CFD-DEM). Their findings were consistent with experimental results from existing literature and provided empirical explanations for the deviations in Terzaghi's theoretical results. Inspired by the numerical analysis results, they established a theoretical model for piping that considers friction resistance.

Y. Guo, S.M.[17] utilized the coupled CFD-DEM method to test and compare spherical and non-spherical particles with different aspect ratios (Figure 4 shows the shapes of different particles in the numerical simulation). The simulation results indicated that grain angularity plays a significant role in the formation of erosion resistance, and they analyzed the impact of sand grain shape on soil erodibility.

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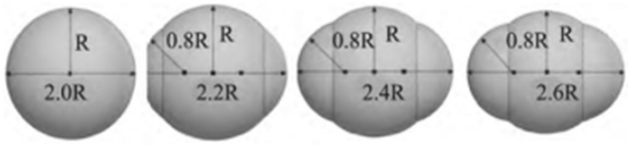

Figure 4. The shape of different particles in a numerical simulation

3. Conclusion

(1) Numerical Simulation Methods for Foundation Piping:

The main methods used for numerical simulation of foundation piping include the finite element method, finite volume method, boundary element method, and discrete element method. Among them, the finite element method is the most used, suitable for analyzing complex foundation systems and piping phenomena, as well as studying various material properties. The finite volume method is suitable for simpler foundation systems with uniform soil properties, while the discrete element method can well describe the matrix-fluid coupling process.

(2) Key Parameters for Numerical Simulation of Foundation Piping:

Key parameters to consider in numerical simulation of foundation piping include the physical and mechanical properties of the foundation and dam, such as elastic modulus and Poisson's ratio; permeability properties, including permeability coefficient and porosity; hydraulic parameters of natural materials, such as refractive index, wave velocity, attenuation coefficient, and characteristic impedance; and geometric and boundary parameters, including dam height, shape, material properties, and cracks.

(3) Development Trends in Numerical Simulation of Foundation Piping:

With advancements in numerical simulation technology, future research on foundation piping numerical simulation will become more accurate and comprehensive. For instance, high-performance computing technology and cloud computing platforms can quickly process large-scale complex piping simulation data. Moreover, more research will explore using artificial intelligence and machine learning algorithms for piping simulation and prediction, improving model accuracy and practicality.

In conclusion, numerical simulation technology provides strong support and tools for piping research. Future studies will leverage modern computational and analytical methods to more thoroughly and deeply investigate foundation piping, providing richer scientific evidence for the operation and safety management of water conservancy projects.

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References

[1] Huo Jiaoping, Zhong Qiming, Mei Shiang: Progress in Numerical Simulation of Earth-Rock Dam Breach Process [J]. People's Yangtze River, 2018, 49(02): 98-103.

[2] Yao Qiuling, Ding Liuqian, Liu Changjun, Zhang Shunfu: Research on Mechanism and Design Criteria for Piping Prevention in Dam Foundations [J]. China Flood and Drought Management, 2022, 32(01): 75-79.

[3] Zhu Wei, Yamakura Kazuya: Mechanism and Control of Foundation Seepage Failure of Dikes [J]. Water Science and Technology Research, 1999, 12(04): 338-347.

ISSN: 2710-0588

[4] Xu Youyuan: Experimental Study and Finite Element Simulation of Piping[D]. Tongji University, 2007.

[5] Liu Changjun, Ning Baohui, Ding Liuqian, et al: Mesh-Free Method Simulation of Piping Erosion Process in Dam Foundations [J]. Water and Energy Science, 2012, 30(04): 50-61.

[6] Jiang Mingjing, Hu Haijun, Murakami A, et al: Numerical Simulation of Piping Phenomena Using Discrete Element Method [C]. Second China Hydropower Geotechnical Mechanics and Engineering Academic Seminar Proceedings (Part II), 2008: 21-26.

[7] Zhou Xiaojie, Jie Yuxin, Li Guangxin: Numerical Simulation of Seepage-Pipe Flow Coupling in Piping [J]. Rock and Soil Mechanics, 2009, 30(10): 3154-3158.

[8] Ren He, Fei Jianbo, Jie Yuxin, et al: Simulation of Piping Development Process Using Natural Element Method [J]. Journal of Hydroelectric Engineering, 2015, 34(07): 21-26.

[9] Wu Mengxi, Deng Qinfang, Huang Yanbei: Numerical Simulation of Dynamic Development of Foundation Piping [J]. Journal of Zhengzhou University (Engineering Edition), 2012, 33(05): 66-71+76.

[10] Hu Yayuan, Ma Pan: Numerical Simulation Study of Two-Dimensional Dam Piping [J]. Engineering Mechanics, 2015, 32(03): 110-118.

[11] Li Xiaoqing, Qi Yang, Tang Xinjun, et al: Particle Flow Simulation of Two Typical Grading Foundation-Filter Systems [J]. Journal of Yangtze River Scientific Research Institute, 2017, 34(04): 92-97.

[12] Wang Shuang, Chen Jiansheng, Zhong Qiming: Numerical Simulation of Dynamic Development of Piping in Multilayer Dam Foundation Structures [J]. Advances in Water Conservancy and Hydropower Technology, 2021, 41(06): 39-45.

[13] Kenichi, Hiroki Hirabayashi: Influence of Grain Properties on Macro Mechanical Behaviors of Granular Media by DEM [J]. Journal of Applied Mechanics, 2006, 9: 623-630.

[14] Luc S, Nadia B, Félix D: Constitutive response predictions of both dense and loose soils with a discrete element model [J]. Computers and Geotechnics, 2021, 135.

[15] Mandie S. Fleshman and John D. Rice. Laboratory Modeling of the Mechanisms of Piping Erosion Initiation [J]. Journal of Geotechnical and Geoenvironmental Engineering, 2014, 140(06).

[16] Junliang Tao, Ph. D, Hui Tao, S. M: Factors Affecting Piping Erosion Resistance: Revisited with a Numerical Modeling Approach [J]. International Journal of Geomechanics, 2017, 17(11): 04017097.

[17] Y. Guo, S. M. ASCE, X. Yu, Ph. D., P.E., M. ASCE: Study of the Particle Shape Influence on Soil Erodibility Using Coupled CFD-DEM Modeling [J]. Geotechnical Frontiers 2017: 40-49.