

Real-Time Simulation of Hydraulic Erosion Based on Soil and Water Conservation Theory and Physical Calculation

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Abstract. Hydraulic erosion stands as one of the most critical influencing factors in geological transformation processes. However, current hydraulic erosion simulations still face several challenges. First, existing computer-based simulations prioritize visual realism while inadequately accounting for authentic physical phenomena and complex environmental factors during hydraulic erosion processes, resulting in insufficient accuracy of simulation outcomes. Secondly, hydraulic erosion involves fluid-solid coupling calculations. Physical-particles-based fluid simulation methods, such as the smoothed particle hydrodynamics (SPH) and position based fluids (PBF) methods, have relatively low computational efficiency in this interaction process.

This paper addresses these two challenges. Regarding accuracy, we comprehensively integrate theoretical frameworks and research achievements from soil and water conservation studies, achieving for the first time a complete hydraulic erosion simulation process encompassing splash erosion and lateral erosion. The simulation system also incorporates multiple environmental factors to enhance accuracy. For efficiency improvement, we introduced an efficient fluid-solid interaction method based on volume maps. This innovation enhances computational efficiency in fluid particle-terrain interactions, making our system one of the first to achieve real-time hydraulic erosion simulation using the PBF particle method.

The proposed method successfully simulates various hydraulic erosion phenomena including splash erosion, vertical incision erosion, lateral erosion, sedimentation and other related phenomena. It achieves real-time computational efficiency in medium-scale scenarios.

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1 Introduction

Hydraulic erosion refers to the detachment, transport, and deposition of surface soil, rocks, and other loose materials caused by the flow of water, such as rainfall and surface runoff. It is one of the primary natural erosion processes responsible for shaping landforms. The simulation of hydraulic erosion is crucial for fields like soil and water conservation, as well as natural disaster prevention and mitigation. Additionally, as a common natural phenomenon, the visual simulation of hydraulic erosion processes has broad application demands in virtual reality, animation, gaming, and other related industries.

However, simulating hydraulic erosion processes is far from straightforward. Hydraulic erosion involves a series of complex phenomena, including splash erosion, vertical erosion, lateral erosion, deposition, thermal erosion, and more. These processes are closely linked to factors such as soil shear resistance strength, soil moisture, soil quality, vegetation, and the angle of repose. Researchers in computer science have long explored hydraulic erosion simulation. Beneš and Forsbach [2] implemented basic fluid motion and hydraulic erosion effects, but this method relied solely on a simple shallow water model for calculations and did not comprehensively account for erosion factors. Cordonnier *et al.* [3] incorporated multiple natural factors influencing erosion, but the approach focused more on macro-level erosion and lacked detailed simulation of hydraulic erosion phenomena, the processes of lateral erosion and splash erosion as well as certain soil properties were ignored. Yu *et al.* [27] proposed a more comprehensive hydraulic erosion simulation system, integrating environmental factors like the angle of repose and soil moisture, as well as modeling lateral erosion-induced river channel widening. However, this method still had limitations: the calculation of channel widening was problematic, splash erosion was not simulated, and the fluid dynamics were oversimplified (fluid particles moved only along slopes). Consequently, the incompleteness of the hydraulic erosion steps and the imprecision of the calculation will lead to errors in the final scene simulation, such as the alluvial fans simulation scene not being realistic enough.

To achieve more accurate simulations of hydraulic erosion processes, it is necessary to model fluid dynamics with higher precision and calculate interactions between fluids and terrain. The SPH method is a widely used strategy for fluid simulation. Krištof *et al.* [10] introduced this method into hydraulic erosion modeling. Compared to shallow water models and simple slope-driven particle methods, the SPH method can more accurately simulate complex fluid motion. However, SPH typically requires tens of thousands of particles to represent fluids, and collision calculations between such a large number of particles and the terrain entail significant computational overhead. This results in low computational efficiency for SPH-based erosion systems, making real-time simulation impractical.

In summary, previous methods suffer from two critical issues: (1) Incomplete consideration of hydraulic erosion processes. Existing approaches primarily focus on vertical erosion by water flow, with limited research on splash erosion and lateral erosion. The calculation of critical factors such as soil shear resistance and angle of repose re-