

RAPID POSITION-BASED SIMULATION OF LANDSLIDE DYNAMICS WITHIN DIGITAL TWIN ENVIRONMENT

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Abstracts: Landslides are destructive geological disasters and mitigating the associated risk has long remained a prominent issue within civilization. In the digital era, the digital twin technology has demonstrated its potential to reduce risk with its characteristics of real scene restoration, timely disaster analysis and information sharing as well as coordinated decision-making. However, one of the dilemmas hindering the use of digital twins in landslide risk management is the prompt and realistic landslide dynamics simulation for real-time interaction in the context of digital twins. Traditional force-based approaches can reasonably reproduce landslide movement, but these methods come with a significant computational burden. To address this challenge, this study leverages a position-based model to simulate landslide dynamics to ensure the simulation efficiency and realism. This method directly manipulates in terms of the particle positions and applies a density constraint to regulate the movement behaviour. Such processing can not only ensure simulation accuracy but also satisfy the requirement for timely interaction. The developed method is validated using a historical landslide case, demonstrating its ability to reasonably replicate the landslide movement at a satisfactory frame per second, thereby enabling real-time interaction.

Keywords: Landslide, digital twin, landslide dynamics, rapid simulation, landslide risk.

1. Introduction

Landslides are devastating natural hazards that can result in substantial harm to people and the economy. Addressing landslide risks has long been a societal concern (Ju et al. 2023; Xiao et al. 2022; Lv et al. 2024). In the digital era, digital twin technologies have become a widely adopted solution for emergency risk mitigation in various engineering disciplines. How to use this technology to help control landslide disasters needs further exploration. One of the bottlenecks is promptly and realistically simulating landslide mobility within the context of a digital twin for timely interaction and decision making. Despite various numerical simulation methods, e.g., finite difference method, smoothed particle hydrodynamics, material point method and discrete element model, have been developed to replicate and study the landslide mobility behavior, embedding them into digital twins for real-time visual interaction remains challenging due to low immersion or low computational efficiency (Ju et al. 2022; Li et al. 2021; Zhao et al. 2024). For instance, it takes about 1 hour to calculate the mobility process of Yu Tung Road landslide using 3dDMM method, whose actual mobility time is only about 60 seconds (Law et al. 2016). To tackle this bottleneck, a novel position-based model is leveraged for landslide dynamics simulation. In contrast to the traditional force-based approaches, such as finite difference models and smoothed particle hydrodynamics, which require solving complex differential equations to update displacements, the position-based method directly manipulates particle positions and focuses on updating particle positions based on constraints. In the context of landslide simulation, a constant density constraint is applied. In this study, the position-based landslide movement simulation is introduced first, followed by the application of this method using a notable historical landslide that occurred in Hong Kong.

2. Position-based Landslide Dynamics Simulation

The position-based method typically represents the objects in terms of particles. For each particle, external forces (e.g., gravity) and internal forces (e.g., friction) are handled separately. Specifically, the particle system is initially updated by external forces based on Newton's second law in each iteration, followed by employing constraints to equivalent internal forces to further update particle positions. Due to its high efficiency, the position-based method has become a popular approach for real-time simulation in digital twin environments, such as in cloth simulation and soft body simulation.

In the case of landslide movement, external forces are mainly gravity and the interface shear resistance between the flow and the bed and internal forces include the internal friction and cohesion between the particles. In the first stage, only gravity is treated as an external force f_{ext} to update particle states. The interface shear resistance is considered after the movement commences and internal forces are equivalent to constraints. Given the incompressibility of landslide fluid, a density constraint is applied to maintain a constant density, thereby regulating the fluid behaviour. For the i th particle, the constant density constraint can be mathematically expressed as:

$$G_i(x) = \frac{\sum_j m_j W(x_i - x_j, r)}{\rho_0} - 1 = 0 \quad (1)$$

where x denotes the positions of the particles, ρ_0 is the rest density (2000 kg/m³ for landslides in this study), r indicates the smoothing length of the Poly6 kernel function $W(\cdot)$, m_j refers to the mass of neighbouring particle j . Since all particles are assumed to have identical mass, m_j is omitted in the subsequent derivations.

To keep density constant, the constraint at position $x+x_i$ should satisfy:

$$G_i(x+\Delta x_i) = 0 \quad (2)$$

Using Taylor polynomial, x_i can be derived as

$$\Delta x_i = \frac{1}{\rho_0} \sum_{j \neq i} (\lambda_i + \lambda_j) \nabla W(x_i - x_j, r) \quad (3)$$

where λ is a scaling factor along the constraint gradient, remaining identical for all particles because of their equal mass. It should be noted that although landslides in reality exhibit non-uniform states, the constant density assumption can improve computational efficiency.

Adjusting particle positions according to the density constraint can lead to issues with particle penetration, which is both unreasonable and unacceptable. To address this, a method based on friction theory is utilized to refine the particle positions. Penetration can be considered a squeezing interaction between particles or between particles and the ground, resulting in normal stress and consequently friction. Utilizing Coulomb's friction law, the frictional position delta for the i th particle can be determined as:

$$\Delta x_{fi} = \eta \times f \times \varepsilon \quad (4)$$

where f is the dynamic friction coefficient; ε is the strain caused by normal stress; $\eta = \frac{\omega_i}{\omega_i + \omega_j}$ is a correction factor related to mass; ω_i and ω_j are the reciprocal of the mass of the i th particle and j th particle.

After implementing the density constraint and friction correction, the particles will be repositioned, and their velocities (i.e., v_i^u) will be calculated based on the rate of position change. To improve fluid dynamics, an artificial viscosity term is introduced to simulate viscosity. In non-viscous flow scenarios, fluid particles can overlap. This additional term helps synchronize the velocities of neighbouring particles, ensuring they move in unison, which is a sensible approach. The viscosity coefficient μ determines the viscosity level; a higher value means a strong viscosity between particles. This model for fluid viscosity has proven effective in enhancing fluid behaviour simulations and ensuring numerical stability:

$$v_i^{new} = v_i^u + \mu \sum_{j \neq i} (v_i^u - v_j^u) \cdot \nabla W(x_i^u - x_j^u, r) \quad (5)$$

The above derivation indicates that the dynamic friction coefficient f and viscosity parameter μ are the key parameters that control the fluid behaviour.

3. Application

During the heavy rainstorm on 23 August 1999, four shallow failures occurred on the natural terrain above Sham Tseng San Tsuen. One has a failure volume of 600 m³ (landslide A in Fig. 1), while others are relatively small, with a total failure volume of only 20 m³ (landslides B-D in Fig. 1). Therefore, the analysis focuses on the movement behavior of landslide A. After detaching from the landslide scar, the debris first reached the opposite bank of the channel, leaving impact marks that reached a height of roughly 3 m. Then it passed through a 10-meter-high waterfall and left superelevation marks at chainage 121m and 217m, which suggest that the corresponding velocities are 11 m/s and 7 m/s respectively. Finally, the landslide hit the kitchen of House No. 38. Fig. 1 is an aerial photograph showing the landslide locations, flow paths and impacted villages and detailed findings of the post-investigation of this landslide can be found in FMSW (2005).

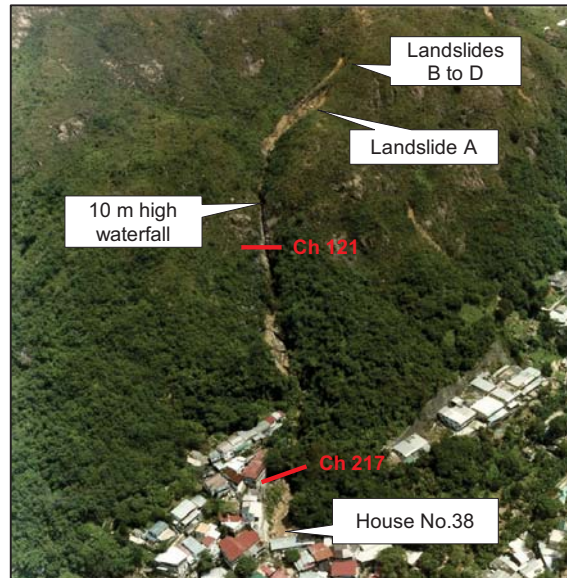


Fig. 1. Aerial photograph of Sham Tseng San Tsuen debris flow.

In the case study, the digital twins of terrain and buildings are first imported to the physical engine to create the digital twin environment (Fig. 2). Then, the position-based method is used for simulation within this digital twin environment. After trying different combination of dynamic friction coefficient f and viscosity coefficient μ , it is determined the best agreement with the field measurements and other numerical simulations can be achieved using f equalling 0.4 and μ equalling 0.1. Koo et al. (2018) utilized LS-DYNA to back-analyse this landslide and an internal friction angle equalling 15° (corresponding to a friction coefficient of 0.27) was suggested to provide a best agreement with the field observations, which is comparable to the proposed friction coefficient of 0.4 in this study. Fig. 2 shows the simulated landslide dynamics in the digital twin environment. About 450 fps are needed to simulate and render the movement of this landslide, satisfying the requirements of real-time interaction (i.e., $\text{fps} > 30$). While it will take several hours to simulate a landslide that has an actual duration of only a few seconds using traditional methods, such as LS-DYNA (Koo et al., 2018). Fig. 3 presents the simulated profiles of landslide front velocity, i.e., the velocity at which the landslide first reaches a certain position, using the position-based method, along with field observations and simulation outcomes produced by 2d-DMM, 3d-DMM and LS-DYNA (Law et al. 2016). The simulation results match well with the field observations and previous numerical simulation outcomes. After a distance of about 120 m, all models exhibit a simulated reduction in flow velocity due to the rugged nature of the channel and the reduced slope gradient.



Fig. 2. Simulated landslide dynamics in digital twin environments.

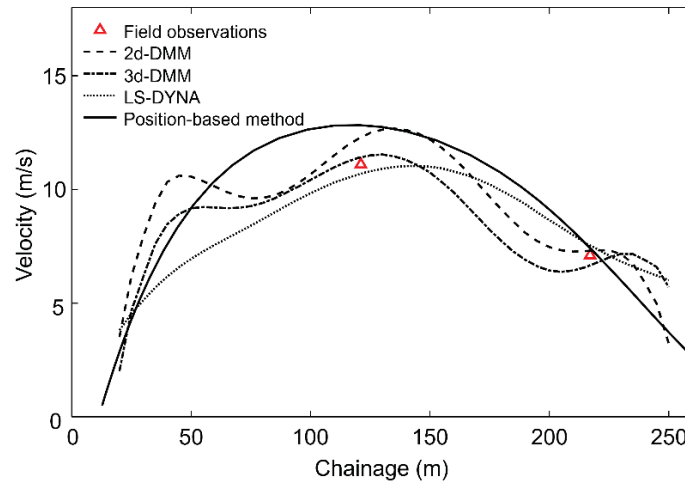


Fig. 3. Back analyzed and field observed front velocities of Sham Tseng San Tsuen debris flow using position-based method, 2d-DMM, 3d-DMM and LS-DYNA.

4. Conclusion

This study leverages a position-based approach for real-time and efficient simulation of landslide dynamics within digital twins. A historical case is back analyzed to illustrate this method. Through directly constraining the particle positions to regulate the landslide movement behavior and incorporating geotechnical parameters (i.e., friction and viscosity coefficients) into the framework, the developed position-based landslide dynamics simulation method can provide real-time and reliable simulation outcomes. The simulation outcomes of the historical case match well with the field observations and other numerical simulation results. Friction coefficient of 0.4 is used for the historical channelized debris flow due to its high mobility, which is comparable to the internal friction angle proposed in Koo et al. (2018), i.e., 15° - 20° for channelized debris flows. The simulation can be effectively executed in the digital twin paradigm with fps of 450 while simultaneously conducting collision detection and rendering, satisfying the 30-fps requirement for smooth real-time interaction.

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