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A hybrid discrete element method with adaptive contact treatment approach for modeling discontinuous rock masses

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ABSTRACT

The Discrete Element Method (DEM) has been widely used to simulate the mechanical behavior of discontinuous rock masses, particularly in underground environments; however, its applicability is often limited to specific contact conditions, such as quasi-static or dynamic interactions. To achieve broad applicability, this study presents a Hybrid Discrete Element Method (hDEM) that adaptively selects between different numerical schemes for contact treatment. The proposed method employs a threshold velocity based on the principle of energy conservation to distinguish between computational schemes at contact: a force-based method is applied to quasi-static contacts, while an impulse-based method is used for dynamic contacts. This approach enables hDEM to accommodate varying contact conditions within a unified framework. Several metrics, validated against theoretical solutions, demonstrate that the proposed approach yields accurate and stable results across different loading scenarios, addressing some of the limitations observed in conventional methods. The relative error of contact force was controlled within 5×10^{-4} % in static tests and the mean absolute error of the velocity was recorded as 3.41×10^{-3} m/s in dynamic tests. In a comparative simulation of tunnel excavation, hDEM achieved results similar to conventional DEM while reducing the number of convergence cycles by 65.4%, highlighting its efficiency and potential as a practical numerical tool for adaptive contact treatment of discontinuous rock masses.

1. Introduction

The stability of tunnels and underground structures is determined not only by continuous deformation in intact materials but also by discontinuous effects caused by structural features such as joints and faults, which play a particularly dominant role in blocky rock masses (Hoek and Brown, 1980). In 1979, Cundall and Strack developed the Discrete Element Method (DEM) to analyze the behavior of discontinuities, which has been extensively applied in various engineering fields (Cundall and Strack, 1979). DEM enables the explicit modeling of rock masses as independent blocks or particles, allowing for effective analysis of discontinuities such as joints and faults (Cundall, 1988; Hart et al., 1988). In the field of geotechnical engineering, this method has been established as a key tool for the analysis of discontinuous rock masses, particularly in highly confined conditions where quasi-static contacts are predominant, e.g., tunnel excavation or pillar stability analysis in underground mines (Jing and Hudson, 2002; Lisjak and Grasselli, 2014; Augrade et al., 2021).

At the same time, considerable efforts have been devoted to improving this approach, primarily addressing the computational costs that represent critical issues when performing these analyses. For instance, calculations based on penetration depth entail substantial computational demand with an increasing problem when solving large-scale models, leading to recurring concerns regarding the practical constraints of DEM (Paluszny et al., 2013; Lisjak and Grasselli, 2014). In addition, incorporating large-scale 3D simulations and coupling with thermodynamic or hydrodynamic calculations causes the simulation time to increase exponentially (Jing, 2003; Lemos, 2012; Wang et al., 2022). On the other hand, penetration depth-based calculations offer only conditional stability when small timesteps are used, making them a major contributor to the overall numerical burden (Augrade et al., 2021).

In recent years, there has been active research on applying hardware acceleration technologies to overcome the aforementioned computational limitations of DEM (Lubbe et al., 2020; Park et al., 2021; Duriez and Bonelli, 2021; Fukuda et al., 2021; Wang et al., 2024; Zhang et al., 2024; Lei et al., 2025). These studies primarily utilize frameworks such as OpenMP and CUDA to perform parallel computing with multi-core CPUs or general-purpose GPUs (GPGPUs), enabling efficient

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