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Review

# Benchmarking the numerical Discontinuous Deformation Analysis method

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ABSTRACT

The Discontinuous Deformation Analysis (DDA) method is an important tool for investigating the dynamics of systems composed of multiple discrete elements such as masonry structures and blocky rock masses. As such it has become a popular investigative tool in geotechnical and rock engineering research. In this paper dynamic verification studies of 2D and 3D-DDA performed by the rock mechanics research group at the Ben-Gurion University of the Negev, Israel (BGU), are reviewed. The analytical verifications developed and reviewed here allow critical assessment of the advantages and limitations of 2D and 3D-DDA, can be used as benchmark tests for attempted modifications to the original DDA code, for calibration of input numerical control parameters, and for quantitative and meaningful comparison with other numerical discrete element methods.



**Contents**



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## 1. Introduction

Discontinuous Deformation Analysis (DDA) is an implicit, discrete element method proposed by Shi [1–4] to provide a tool useful for investigating the dynamics of blocky rock masses and systems composed of multiple blocks. The 2D-DDA was proposed first, at the 1980s at UC Berkeley, and the 3D-DDA was published later [5]. A good review of the essentials of DDA is provided by Jing [6]. Reviews of DDA within the scope of other numerical methods used today to solve problems in rock mechanics and rock engineering are provided by Jing [7], Jing and Hudson [8] and Jing and Stephansson [9]. Many verification and validation studies have been performed to test the capability of DDA to solve static as well as dynamic problems since its publication. A comprehensive review of 2D-DDA validations is provided by MacLaughlin and Doolin [10]. The 3D-DDA, being a more recent development, has not been verified extensively and this paper presents new and useful validations also of 3D-DDA.

Many research groups have made modifications to the original code developed by Shi [1,3,4] in an attempt to better address some of the fundamental issues in DDA. For example, Lin et al. [11] modified the original contact model of DDA, which is based on the penalty method, by adopting the Lagrange type approach. Ning et al. [12] modified the contact algorithm of DDA by adopting the Augmented Lagrangian method. Bao and Zhao [13,14] have made some enhancements to the vertex to vertex contact. In an attempt to overcome the DDA simply deformable blocks assumption and therefore uniform distribution of stresses within blocks, Shi [15] developed the Numerical Manifold Method, using superposition of a mathematical cover over the physical mesh of the blocks. Bao and Zhao [16] have integrated the advantages of both DDA and the finite element methods (FEM), and developed the hybrid nodal-DDA (NDDA), thus improving the accuracy of stress distribution and allowing for crack propagation within blocks. Jiao et al. [17] developed a two-dimensional contact constitutive model to simulate the fragmentation of jointed rock. Several other research groups have developed higher order DDA codes to address this issue e.g. [18]. Jiao et al. [19] applied a viscous boundary in DDA based on the standard viscous boundary condition provided in the original DDA formulation, in order to deal with dynamic wave propagation problems. Later on Bao et al. [20] implemented new viscous boundary conditions to the 2D-DDA, in order to improve the absorbing efficiency. Mikola and Sitar [21] developed a 3D-DDA formulation using an explicit time integration procedure, and a different contact detection algorithm. Kim et al. [22] and Jing et al. [23] have made a modification where they compute water pressure and seepage through rock mass, this way coupling fluid flow in fractures. More recent implementations of hydro-mechanical coupling in DDA was developed by Chen et al. [24] and Ben et al. [25]. Koyama et al. [26] combined the DDA and the finite element method for fluid flow simulation to model the interaction between solid particles movement and fluid flow. Wu et al. [27] developed a post-contact adjustment method to overcome issues when addressing rock fall problems in the original code. A model for cable bolt–rock mass interaction was integrated with DDA by Moosavi and Grayeli [28]. Other useful developments and applications of DDA are summarized in a series of ICADD proceedings (International Conference on Analysis of Discontinuous Deformation) published biannually since 1995.

In this paper we review illustrative benchmark tests performed by members of the rock mechanics group at the Ben-Gurion University of the Negev (BGU), with the original codes of 2D and 3D-DDA. These tests could be performed in every development of the DDA code, for verification purposes. We compare all benchmark tests reported here with analytical solutions, some developed at BGU and some adopted from existing publications. The authors do acknowledge other verification studies performed by other research groups, such as the extensive study of sliding blocks performed at Nanyang Technological University in Singapore [29], slope stability kinematics [30] and analysis of three-hinged beams [31] performed at U.C. Berkeley, and more, but here only verifications resulting from BGU research are discussed, for brevity. Verifications that have already been published are briefly summarized. New verifications that have never been published are presented more thoroughly.

We begin with a brief summary of DDA fundamentals in Section 2, followed by review of published verifications of 2D-DDA in Section 3, and presentation of published and newly developed results of 3D-DDA in Section 4. Summary of results and conclusions are presented in Section 5.

## 2. DDA fundamentals

DDA considers both statics and dynamics using a time-step marching scheme and an implicit algorithm formulation. The static analysis assumes the velocity of the different block elements is zero at the beginning of each time step, while the dynamic analysis assumes the velocity at the beginning of a time step is inherited from the previous one. The criterion for convergence in DDA is that there will be neither tension nor penetration between the blocks. These two constraints are applied using a penalty method, where stiff springs are attached to the contacts. Extension or compression of the springs are energy consuming, therefore the minimum energy solution utilized in DDA assures no penetration or tension between the blocks.

In the original code of the DDA, a damping submatrix was not incorporated in the equilibrium equations. There are two ways to introduce damping in the original code: the time step marching