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Introduction

We present results from a parameter study investigating the stability of underground structures in response to ground shock. Direct simulation requires detailed knowledge of both the facility itself and the surrounding geology. In practice, however, key details (joint spacing, joint stiffness, reinforcement) may not be available. Thus, in order to place bounds upon the predicted behavior of a given facility, an extensive series of simulations representing different realizations may be required. We will discuss the distinct element method (DEM) with particular emphasis on techniques for achieving improved computational efficiency, including the handling of contact detection and approaches to parallelization. Some continuum approaches to the simulation of underground facilities are discussed along with results from underground explosions. Finally, our DEM code is used to simulate dynamic loading of several generic subterranean facilities in hard rock for a range of joint properties and sources, demonstrating the suitability of the DEM for this application.

Continuum mesh-based methods have been applied successfully to many problems in geophysics. Even if the geology includes fractures and faults, when sufficiently large length scales are considered a continuum approximation may be sufficient. However, a large class of problems exist where individual rock joints must be taken into account. This includes problems where the structures of interest have sizes comparable with the block size. In addition, it is possible that while the structure may experience loads which do no measurable damage to individual blocks, some joints may fail. A continuum, mesh-bashed treatment of such systems is usually inappropriate.

We employ the Distinct Element Method (DEM), as defined by Cundall and Hart (1992). By nature, the Distinct element method can readily handle large deformation

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on the joints. In addition, the method detects all new contacts between blocks resulting from relative block motion. The Lagrangian nature of the DEM simplifies tracking of material properties as blocks of material move. It is also possible to guarantee exact conservation of linear and angular momentum. The joint models can be very flexible and can incorporate experimentally observed effects such as, cohesion, joint dilation, friction angle, and hysteresis(Heuzé et al. 1993).

The DEM has been applied to a wide range of problems in geomechanics. For example, Antonellini and Pollard (1995) simulated the formation of shear bands in sandstone using the DEM. Morgan (1999a),Morgan (1999b) applied the DEM to the mechanics of granular shear zones. Heuzé et al. (1993) used the DEM to analyze explosions in hard rock. Cundall (2001) reviews the application of the DEM to simulation of granular material and rock.

Our DEM Implementation

We use the "Common-Plane"(Cundall 1988) approach to reduce the complexity of the contact detection algorithm. The iterative procedure of the common-plane approach is very easy to implement and can be very efficient for many classes of problem. Typically, the common-plane orientation from the previous time-step provides a good initial guess of the current orientation. Provided the appropriate normal of the contact has not changed much between time steps, the iterative procedure converges rapidly.

The number of distinct elements used in a single simulation is limited by the available computational power. We chose to use an approach similar to Cleary and Sawley (1999) and parallelized the DEM through spatial domain decomposition. The entire problem domain is divided into nearest neighbor cells which are used to identify neighboring blocks which are potential contacts. Each processor is assigned a contiguous region of nearest neighbor cells. Communication occurs via message passing (MPI) at the start of each time step. All blocks within neighboring cells are copied between processors. To reduce the amount of time wasted during communication, each processor performs calculations on blocks which do not directly interact with neighboring processors while communication occurs. Duplicate calculations are performed on each processor in the region of overlap where blocks are copied back and forth. Consequently, speedup is best for larger problems where the region of overlap between processors is a smaller fraction of the total work performed.

Simulations of Underground Structures

To predict damage sustained by underground structures, several coupled regions must be modeled. In the immediate vicinity of an explosion, the ground shock is sufficient to rubblize the rock, material strength is irrelevant, and the material behavior is hydrodynamic. Deeper into the rock, material strength becomes important. Finally, in the vicinity of the facility, the detailed structure of the rock mass and the excavation itself are important.

Traditionally a rock mass is deemed to fail when the strength of the material is exceeded. Failed rock is no longer able to withstand load without undergoing inelastic strains. However, hard rock strength increases markedly with increased pressure and yet it has been observed that functional damage or even complete tunnel collapse can occur at stress levels far below those previously thought to be required. For example, Figure 1 shows the collapse of an excavation in tuff subjected to loads significantly lower than the compressive strength of the rock. The discrete nature of the rock mass is evident and failure has occurred through block displacement.

Clearly, the orientation, spacing, and shear strength of geologic discontinuities (joints) can control the behavior of a tunnel. Hard rock joints dilate strongly before reaching peak strength, after which the strength drops rapidly with increased loading. As a result of the controlling effects of the joints it is not possible to estimate tunnel response via continuum based analysis alone.

Our approach is to combine continuum and discrete numerical methods. Typically, the depth of the tunnel is large compared with the size of the blocks making up the rock, and continuum approaches have been very successful in reproducing measured attenuation rates from the source. Lomov et al. (2001) present an approach for accurately modeling projectile penetration and explosions in rock media. Using an Eulerian code (GEODYN) Lomov et al. (2001) fit a constitutive model (Rubin et al. 2000) to peak velocity and displacement attenuation data from tamped (buried) nuclear explosions in granitic rock. This continuum treatment was able to reproduce peak velocity and displacement from tamped explosions in granitic rocks to within a factor of two over *ten* orders of magnitude in yield.

The velocity or stress history predicted by GEODYN at a given point can be used to provide boundary conditions for a DEM simulation of the response of the underground facility. For example, Figure 2 shows a tunnel in jointed rock. The average block size is approximately 1 m. The jointed rock mass is confined by 7.5 MPa of lateral and vertical stress. The rock island was subjected to a velocity pulse obtained from a GEODYN simulation of a surface explosion, with a peak velocity of 4.21 m/s. This

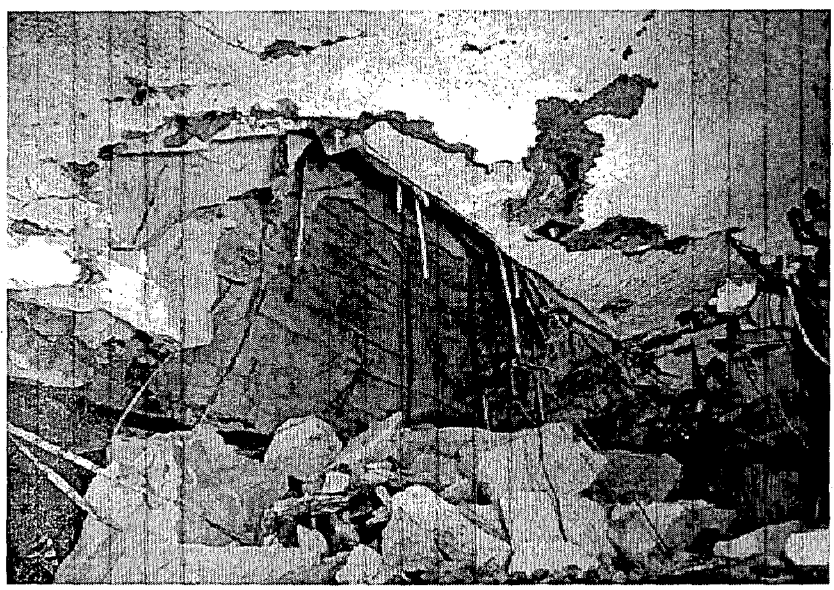

FIG. 1. An excavation, reinforced with rockbolts within tuff, collapsed at low stress.

preliminary calculation indicates that at early times, some blocks attain velocities up to three times the peak velocity applied to the boundary.

We have also performed simulations of more complete underground structures. Figure 3a shows a generic underground facility in a jointed rock island. The simulation using our DEM code predicts that a portion of the roof will collapse, rendering the facility unusable (Figure 3b). The joint structure is realistic, with non-orthogonal joint planes. Blocks are free to move and make new contacts with other blocks in the simulation.

In practice, however, only limited knowledge of local fault zones may be available. To provide bounds on the response, one must study a range of probable fault geometries. That is, a stochastic analysis with many realizations is required to obtain adequate statistics to bound results. Future work will include parameter studies to investigate the range of tunnel responses for given variability of joint properties.

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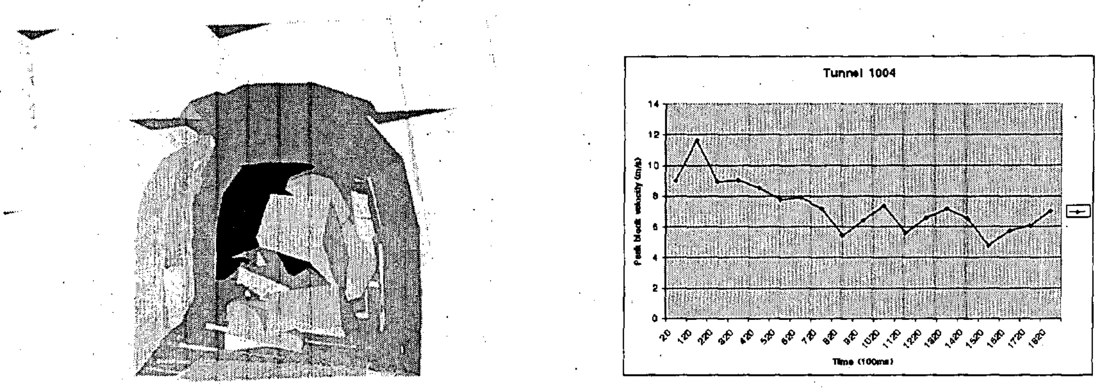

(a) (b)

FIG. 2. (a) A simulation of a tunnel segment in a jointed rock island subjected to a peak velocity of 4.21 m/s. (b) Peak block velocity as a function of time. The simulation predicts that some blocks may attain velocities up to 3 times the peak boundary velocity.

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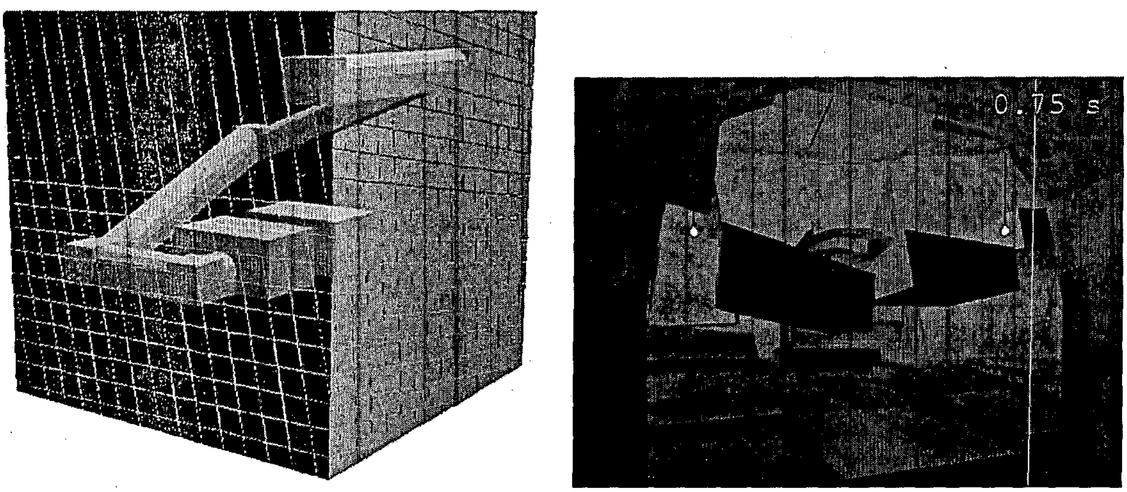

(a) (b)

FIG. 3. Simulation of a generic underground facility in a jointed rock island.