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# Simulations of Fracture and Fragmentation of Geologic Materials using Combined FEM/DEM/SPH Analysis

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## ABSTRACT:

An overview of the Lawrence Discrete Element Code (LDEC) is presented, and results from a study investigating the effect of explosive and impact loading on geologic materials using the Livermore Distinct Element Code (LDEC) are detailed. LDEC was initially developed to simulate tunnels and other structures in jointed rock masses using large numbers of polyhedral blocks. Many geophysical applications, such as projectile penetration into rock, concrete targets, and boulder fields, require a combination of continuum and discrete methods in order to predict the formation and interaction of the fragments produced. In an effort to model this class of problems, LDEC now includes implementations of Cosserat point theory and cohesive elements. This approach directly simulates the transition from continuum to discontinuum behavior, thereby allowing for dynamic fracture within a combined finite element/discrete element framework. In addition, a Smooth Particle Hydrodynamics (SPH) capability has been incorporated into LDEC, permitting the simulation of fluid-structure interaction. We will present results from a study of detonation-induced fracture and fragmentation of geologic media surrounding a tunnel using LDEC.

## INTRODUCTION:

A wide range of geological applications involve materials or systems that are discontinuous at fine enough scale of observation. While some systems may be intrinsically discontinuous, other discontinuous systems are best approximated by a continuum, a discontinuum, or a combination of the two, depending upon the specific information of interest. Continuum, mesh-based methods have been applied successfully to many problems in geophysics, and a continuum approximation may be adequate when sufficiently large length scales are considered—even if the geology includes fractures and faults. However, a large class of problems exists where individual rock discontinuities must be taken into account. This includes problems whose structures of interest have sizes comparable with the block size, or when the structures experience loads that do no measurable damage to individual blocks, but deformation along material discontinuities still leads to structural failure. In these cases, a purely continuum, mesh-based treatment is usually inappropriate. Field tests indicate that structural response can be dominated by the effect of preexisting fractures and faults in the rock mass. Consequently, accurate models of underground structures must take into account deformation across fractures and not simply within the intact portions of the rock mass.

The distinct element method (DEM) is naturally suited to simulating such systems because it can explicitly accommodate the blocky nature of natural rock masses. Cundall and Hart (1992) review a number of numerical techniques that have been developed to

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simulate the behavior of discontinuous systems using DEMs. However, many applications in geophysics require a combined continuum-discontinuum treatment for a complete solution. For example, projectile penetration into a rock or concrete target requires continuum-discontinuum analysis in order to predict the formation and interaction of the fragments produced. Underground structures in jointed rock subjected to explosive loading can fail due to both rock motion along preexisting interfaces and fracture of the intact rock mass itself. In such applications, it is insufficient to simply predict whether or not the rock mass will fail—instead, the critical issues are how fracture and discontinuous interaction lead to the ultimate fate of rock fragments.

To answer these questions, a continuum-discontinuum capability was developed by incorporating finite element analysis and nodal cohesive elements into the Livermore Distinct Element Code (LDEC). This computer code was originally developed by Morris et al. (2002) to simulate the response of jointed geologic media to dynamic loading. Subsequently, LDEC was extended to include Finite Element-Discrete Element transition (Morris et al., 2006). LDEC has also been extended to include a nodal cohesive element formulation that allows the study of fracture problems in the continuum-discontinuum setting with reduced mesh dependence (Block et al., 2007). Most recently, a Smooth Particle Hydrodynamics (SPH) capability was incorporated into LDEC, permitting the simulation of a detonation within the LDEC framework. This paper presents recent results using LDEC to simulate fracture and fragmentation in response to explosive loading employing the fully coupled SPH module within LDEC.

## TREATMENT OF GEOLOGIC MEDIA USING LDEC:

In the simplest case, the Livermore Distinct Element Code can be run in a rigid-block mode, so that all deformation in the system is lumped into the contacts. The most complicated aspect of the code is then related to contact detection. In general, the equations of motion of the elements are determined in a standard manner by integrating vector equations for both the center of mass of each element and an orthonormal vector triad that determines its absolute orientation. Contact detection monitors how the connectivity changes as a result of relative block motion. The Lagrangian nature of the DEM also simplifies tracking of material properties as blocks move, and it is possible to guarantee exact conservation of linear and angular momentum throughout the computation.

Deformation within the individual blocks is often introduced into DEM formulations by using additional standard continuum discretization, such as finite differences or finite elements. In Morris et al. (2004), it was observed that the theory of a Cosserat point (Rubin, 1995, 2000) can model each element as a homogenously deformable continuum. A Cosserat point describes the dynamic response of the polyhedral rock block by enforcing a balance of linear momentum to determine the motion of the center of mass, as well as three vector balance laws of director momentum to determine a triad of deformable vectors, which model both the orientation of the element and its deformation. The response of the deformable polyhedral block is modeled explicitly using the standard nonlinear constitutive equations that characterize the original three-dimensional material.

Consequently, the constitutive equations for the contact forces at the joints become pure measures of the mechanics of joints.

The version of LDEC that includes homogeneously deformable Cosserat points has been used successfully to model a number of problems of physical interest (Morris et al, 2004). However, this approach is inappropriate for problems whose length scales of interest (such as a tunnel diameter) are only slightly greater than the block size. This deficiency was overcome by internally discretizing the polyhedral blocks with a collection of smaller tetrahedral elements. The numerical solution procedure depends on nodal balance laws to determine the motion of the four nodes of each tetrahedral element, similar to that described above for the motion of blocks. In general, the accelerations of the nodes of a particular element are coupled with the nodes of the neighboring elements. However, the director inertia coefficients in the theory of a Cosserat point can be specified so that these equations become uncoupled. This form corresponds to a lumped mass assumption and is particularly convenient for wave propagation problems using explicit integration schemes because it does not require the inversion of a mass matrix.

In continuum regions, where the nodes of neighboring elements are forced to remain common (i.e., unbreakable), the Cosserat point formulation is basically the same as standard finite element models (FEM) that use homogeneously deformable tetrahedral elements. In this case, the computational effort in LDEC is significantly reduced: many nodes are shared and there is no need for contact detection on shared element surfaces. While standard finite element formulations are based on shape functions and weighting functions, the latest version of LDEC utilizes balance laws for the directors of each Cosserat point (associated with the positions of the nodes of the tetrahedral elements). LDEC can be run simultaneously in DEM and FEM-like modes, dynamically blending continuum and discrete regions, as necessary.

## SMOOTH PARTICLE HYDRODYNAMICS:

Smooth particle hydrodynamics (Monaghan, 1992) is a Lagrangian CFD technique that has found a wide range of applications, including free-surface flows (Monaghan, 1994) and elasticity (Gray et al, 2001). It has also been applied to low Reynolds number flows (Morris et al, 1997), including surface tension (Morris, 2000).

Using SPH a fluid is represented by particles, typically of fixed mass, which follow the fluid motion, advect contact discontinuities, preserve Galilean invariance, and reduce computational diffusion of various quantities including momentum. The equations governing the evolution of the fluid become expressions for interparticle forces and fluxes when written in SPH form. The Lagrangian nature of SPH facilitates coupling to other Lagrangian techniques, such as the DEM.

To simulate fully-coupled interactions between fluids and solids we need to introduce a force between the SPH particles and the DEM polyhedral blocks. This work employs a penalty method (it is also possible to introduce "ghost" SPH particles within the DEM elements). A signed distance, $D$, of all SPH particles in the vicinity of a given block above each face of the block is calculated. A linear force is applied to the particle that is proportional to the distance the particle penetrates within a chosen stand-off distance, $D_0$, of the block:

$$\mathbf{F}_a^{BC} = K_a^{BC}\left(D - D_0\right)\mathbf{n} \qquad \text{EQ 12}$$

where

$$K_a^{BC} = A\frac{m_a {c_a}^2}{h^2} \qquad \text{EQ 13}$$

$A$ is a non-dimensional constant that controls the amount of penetration of the particles within the stand-off distance $D_0$ and $\mathbf{n}$ is the normal to the block. The particle mass, soundspeed and smoothing length are denoted by $m_a$, $c_a$ and $h$ respectively.

## VERIFICATION SIMULATION: EXPLOSION IN LIMESTONE:

To verify the implementation of SPH and coupling with the FEM capability under dynamic loading in LDEC we simulated a spherical explosion in Limestone and compared results with an established Eulerian adaptive mesh code, GEODYN. The computational domain consisted of a 19.8mm radius sphere of CompB explosive embedded in a 100mm radius sphere of Limestone. At t=0, the entire volume of explosive is detonated. The GEODYN code was run in 1-dimensional mode, with a cell size of 1mm. The LDEC code was run in 3-D mode, with the Limestone discretized into tetrahedral elements of side length approximately 10mm. The high explosive in the LDEC simulation was represented by SPH particles initially placed on a cubic lattice of spacing 2mm.

Figure 1 shows a comparison between the LDEC simulation and Geodyn at several distances from the source. The two methods agree well in terms of peak velocity, with the lower resolution LDEC simulation showing somewhat slower rise times. In addition, the LDEC simulation exhibits some oscillation behind the initial pulse with a period that corresponds to oscillation of the cavity.

## SIMULATIONS OF A TUNNEL OPENING IN INFREQUENTLY JOINTED ROCK:

Initial applications of LDEC typically involved a tunnel in heavily jointed, hard rock, where the tunnel diameter was spanned by many blocks (Morris et al. 2002, 2004). It is then appropriate to simulate the rock mass using a “tight” structure consisting of polyhedral blocks that are either rigid or homogenously deformable (with deformable points of contact in either case). In contrast, this paper considers the response of a tunnel to a detonation, where the joints are sufficiently infrequent so that the predominant failure mechanism is block breakage rather than intact rock displacement. Detonation is simulated using SPH, demonstrating the fully-coupled, SPH-FEM-DEM capability.

This preliminary simulation (see Figure 2) is performed in two dimensions. The geology consists of blocks of limestone, measuring 1.83 m wide, by 0.30 m high, surrounding a tunnel measuring 1.23 m by 1.23 m, located 1 m below the surface. The tunnel is subjected to loading from a cylinder of CompB high explosive located near the tunnel of radius 0.25m, centered 0.5 m above the ground. The calculation was performed in two stages. Initially, LDEC was run with deformable blocks of limestone internally discretized into 10 cm tetrahedral elements. In this mode of operation, the time step is quite short so that deformation within the 10 cm elements can be captured. After 1 ms, the LDEC calculation was switched over to rigid-block mode, which ignores internal modes of the elements, leading to an increase in the size of the time steps. This allows us to investigate the flow of rubble into the tunnel over longer time scales. Subsequent panels in Figure 2 depict a portion of the roof collapsing into the tunnel.

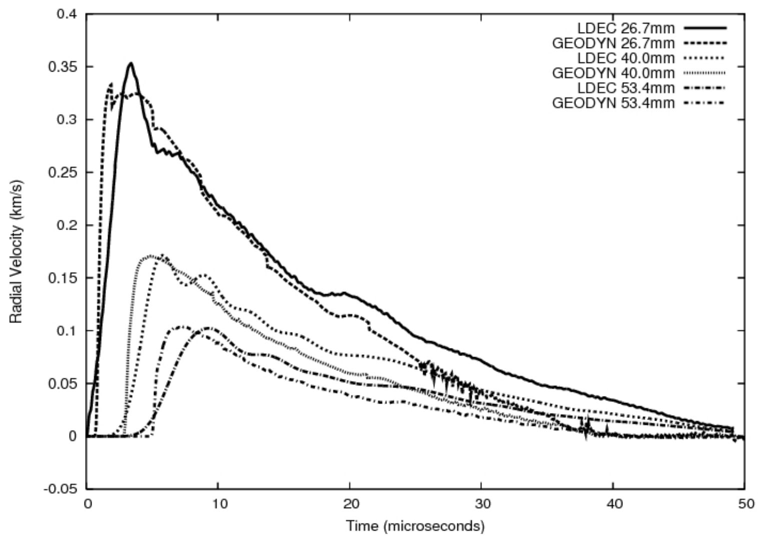


**Figure 1 Comparison of a 3-D LDEC simulation of a spherical detonation in Limestone with a high resolution 1-D simulation using GEODYN**

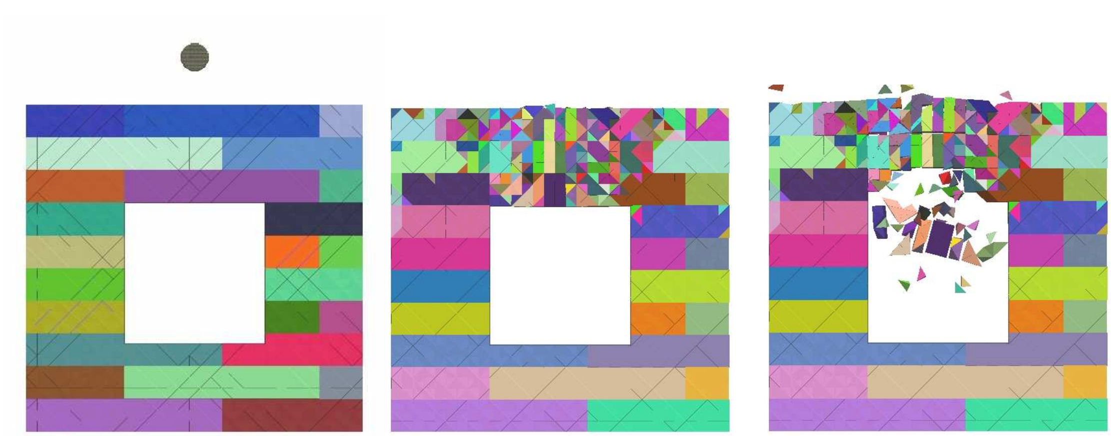

**Figure 2: The infrequently jointed model is displayed at far left, with individual blocks colored randomly to emphasize joint locations. The simulation results at 1 ms (middle) show that the initially intact blocks above the tunnel have fragmented. The simulation results at 1 ms (middle) show that the initially intact blocks above the tunnel have fragmented. The simulation at and 100 ms (far right), indicates that a portion of the roof collapses into the tunnel.**

## CONCLUSIONS:

Previous work has demonstrated that the Livermore Distinct Element Code is capable of simulating the dynamic response of elaborate, underground facilities and tunnel systems to shock-wave loading (Morris et al, 2006). Such large-scale studies allow the investigation of the interaction between different parts of the facility, and the study of how these interactions lead to tunnel collapse and overall failure. In contrast, this paper has demonstrated the internal discretization of the LDEC blocks into tetrahedral elements for cases where the predominant failure mechanism is block breakage rather than intact rock displacement. The addition of an SPH capability allows us to simulate detonation close to a tunnel opening, including fracture and fragmentation.

The current version of LDEC provides simultaneous DEM and FEM-like domain partitioning, as well as the possibility of converting between the two modes dynamically. Future work will focus on combining the DEM, FEM, and cohesive elements together to produce an efficient formulation that is both accurate and robust. Specifically, it is anticipated that this effort will produce the capability of large-scale simulations of fragmentation and dynamic fracture of an important class of problems that are simply beyond the scope of current codes.

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