Simulation of an extensive underground structure subjected to dynamic loading using the distinct element method

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Abstract

We present results from an investigation into the stability of underground structures in response to explosive loading. Field tests indicate that structural response can be dominated by the effect of pre-existing fractures and faults in the rock mass. Consequently, accurate models of underground structures must take into account deformations 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. We will discuss details specific to our implementation of the DEM and summarize recent results.

Keywords: Numerical methods; Geophysics; Structural stability; Fractures; Joints; Distinct element methods

1. Introduction

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 can be sufficient. Using this approach, the response of field-scale rock masses can be modeled using standard elastic-plastic continuum equations. However, for problems where the structures of interest have sizes comparable with the blocks formed by fractures, individual rock discontinuities must be taken into account. In addition, it is possible that while the structure may experience loads that do no measurable damage to individual blocks, deformation along the discontinuities may lead to structural failure (see Fig. 1). We have developed the Livermore Distinct Element Code (LDEC) for simulating the dynamic response of structures within jointed rock masses [1].

LDEC provides several different element types for simulating different rock masses: rigid blocks, uniformly deformable blocks and finite elements. The original implementation of the DEM with LDEC assumed rigid blocks, with the compliance of the system entirely modeled by deformable points of contact between the blocks. This element type is most suited to simulations of fractured hard rock, such as granite.

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Fig. 1. The blocky nature of the rock mass is evident in the collapse of this cavern in Tuff. This cavern collapsed at stresses below the yield strength of the intact rock mass.

The uniformly deformable block implementation within LDEC is discussed in detail by Morris et al. [1]. Most commonly, deformation within the individual blocks is introduced into DEM formulations by using additional standard continuum discretization (for example, Cundall [2]). With LDEC, the blocks are modeled using the theory of a Cosserat point [3,4]. Within the context of the LDEC code the motion of a rigid block is determined by integrating equations for the position of the block's center of mass and for a rigid

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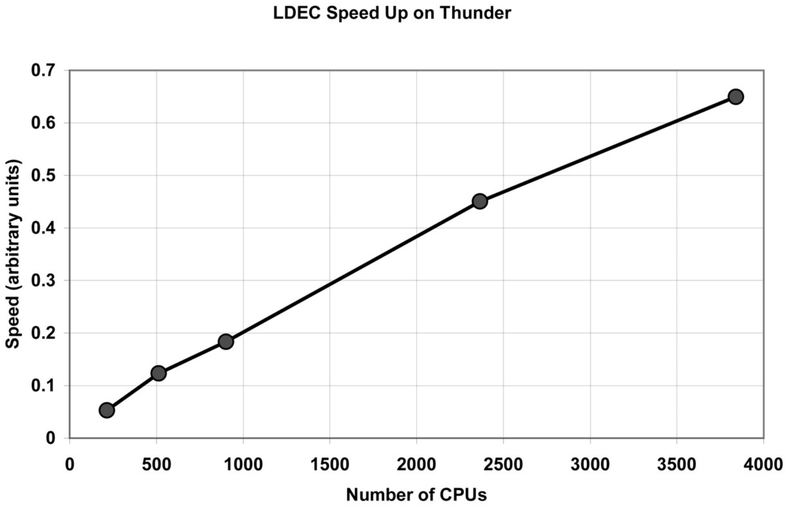

Fig. 2. Plot of speed versus number of CPUs on the Thunder supercomputer for a test problem containing 8 million rock blocks. LDEC exhibited excellent scaling from 256 to 3840 processors.

body triad of vectors that characterizes the block's orientation in space. This theoretical structure makes it particularly easy to implement the simplest form of the theory of a Cosserat point which models purely homogeneous deformations. This is because the kinematics of the present deformed configuration of the block are characterized by the position vector of the block's center of mass and a triad of three deformable director vectors. Consequently, the blocks require no internal discretization, and the computational effort is comparable to that of the rigid block implementation.

LDEC also supports finite element analysis using tetrahedral elements. This formulation supports dynamic fracture of the finite element mesh and permits simulation of mixed continuum–discontinuum problems. In addition, LDEC has been coupled with the DYNA-3D code to simulate the response of reinforced tunnels [1].

2. Discussion

In this paper we focus on recent results obtained using LDEC to simulate the response of unreinforced underground tunnels to dynamic loading. In practice the extent of the facility considered is limited by the computational effort required to simulate the necessary number of rock blocks. We recently performed a series of simulations on the 'Thunder' supercomputer at Lawrence Livermore National Laboratory. Thunder provides a maximum of 4008 itanium processors for computations. This allowed us to consider models of greater size and complexity than had previously been possible. For example, Fig. 2 shows the speedup obtained with LDEC on Thunder. Our solution domain spanned 60m in each direction and encapsulated a generic facility that included several tunnel sections and a lift shaft (see Fig. 3).

Several geologic models were considered as part of this study. In particular, the behavior of regular, persistent joints was compared with the effect of non-persistent randomized joints. For this study, the rigid block capability was used to model hard rock and emphasize the role of joint geometry. Figure 4 shows the randomized jointing that was typical of the non-persistent model geology. In both cases discussed here, the joint patterns resulted in typical block sizes of 30cm. Consequently each model contained approximately 8 million individual polyhedral rock blocks and approximately 100 million contact elements, making these the largest simulations of this type performed to date. The

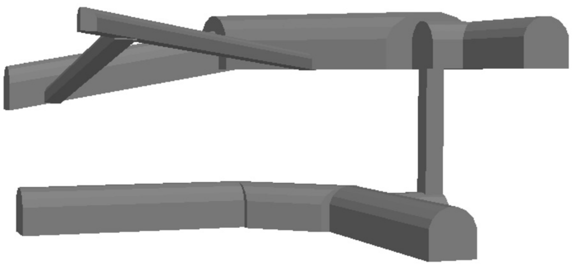

Fig. 3. Generic facility model including several tunnel sections and a lift shaft. The facility spans 60m and is 50m below the surface.

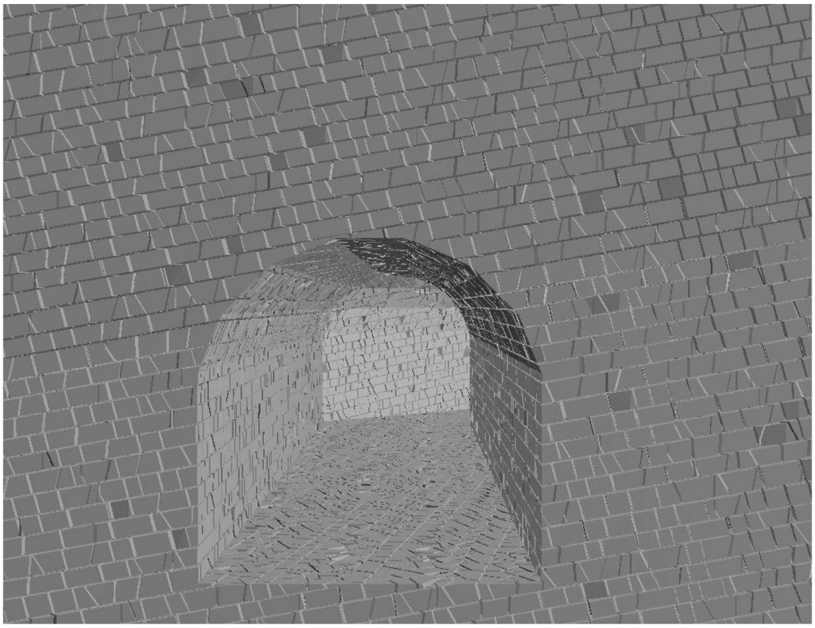

Fig. 4. The non-persistent randomized geology in the vicinity of one of the tunnels. The near-horizontal joint set persists through the model; however, the joint sets in the near vertical direction persist only through several consecutive layers at a time.

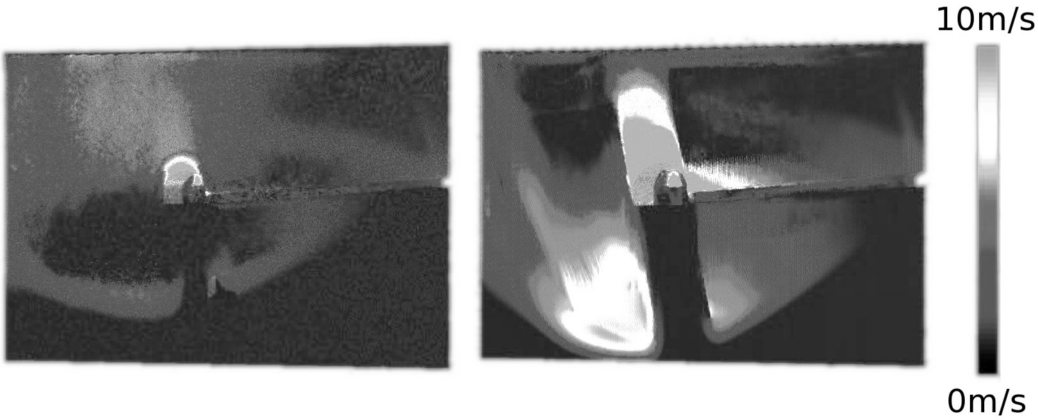

Fig. 5. The velocity magnitude for the two models at 30ms. The non-persistent, randomized geology model (left) and regular jointed model (right) exhibit fundamentally different responses to loading.

facilities were subjected to loading corresponding to one kiloton at the surface 50m above.

Figure 5 compares the velocity fields of the two simulations at 30ms. The results obtained for the regular, persistent joint set and irregular, non-persistent model differed in several key ways:

1. The regular model exhibited strong anisotropy. Since the joints are weak under shear loading, the regular, persistent joint sets tend to channel the waveform, resulting in variations in wavespeed with direction of propagation.
2. The irregular model exhibited higher attenuation. Again, because the joints are weak under shear loading, the irregular joint structure results in more plastic deformation on the joints and, consequently, more attenuation.
3. Persistent joints allow shear motion along the entire length of the computational domain, resulting in large ‘chimney’ effects above collapsed tunnels’ sections.
4. The irregular model resulted in more diffraction of waves around cavities in the rock mass.

Fig. 6. Snapshots of the largest room at 0ms and 200ms. The simulation predicts that this large room within the facility would completely collapse under the applied loading.

Figure 6 shows two snapshots of the collapse of the largest room within the facility from the irregular, non-persistent joint set simulation. The response of the entire facility may be summarized:

1. The largest room within the facility is totally collapsed.
2. The narrowest access tunnels experience minimal damage.
3. The midsize tunnels show a range of damage, with most damage occurring in tunnel sections containing a junction with another tunnel or lift shaft. This is consistent with the tunnel junction compromising the tunnel strength.

3. Conclusions

The Livermore Distinct Element Code (LDEC) has simulated the response of large-scale facilities to dynamic loading. Such large-scale studies allow us to investigate the interaction between different parts of the facility. Results obtained highlight the importance of including realistic, irregular, non-persistent joint sets.

Acknowledgment

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