**INSIGHTS INTO THE RESPONSE OF TUNNELS IN JOINTED ROCKS UNDER DYNAMIC LOADING**

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Workshop on Rock Dynamics
4th Asian Rock Mechanics Symposium
Singapore, November 7, 2006



## Outline

The presentation will cover the following:

- Failure of tunnels under dynamic loading (coal bumps, rock bursts, explosions)
- Modeling of dynamic tunnel response
- A glimpse into the future of discrete element simulations
- Summary - Conclusions



## Some ground truths to live with

The term “jointed rock masses” describes just about any rock mass. Rock formations are transected by many geologic discontinuities (faults, shears, joints, etc…).

It will be demonstrated, that geologic discontinuities have a considerable influence on the response of underground structures to ground shock.

It follows that when one tries to assess the damage created by shock waves on underground structures:
- the knowledge of the subsurface geology is of critical importance, and
- the uncertainties in effects estimates can be very significant.



## Underground failures in jointed rocks

Pillar damage in an oil shale mine, Piceance Basin, CO

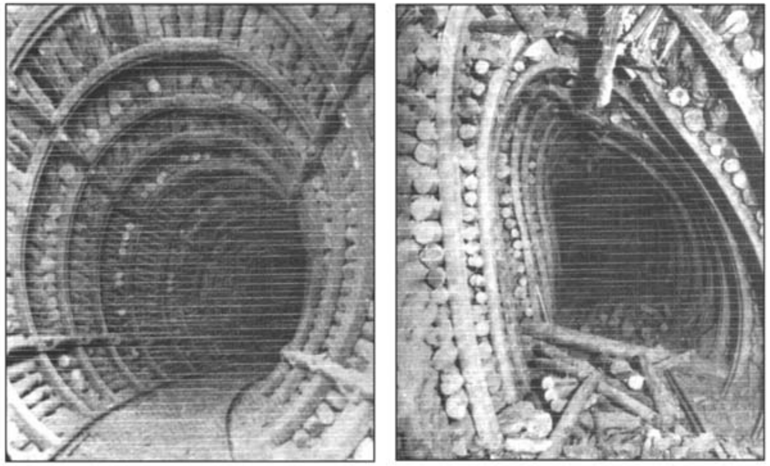
Explosion-driven floor failure in a drift in tuff, Nevada Test Site

## Underground failures in jointed rocks (cont.)

Effects of a bump in a coal mine, Belgium. Note the buckling of thin rock layers.
Courtesy of P. Stassen, 1985.



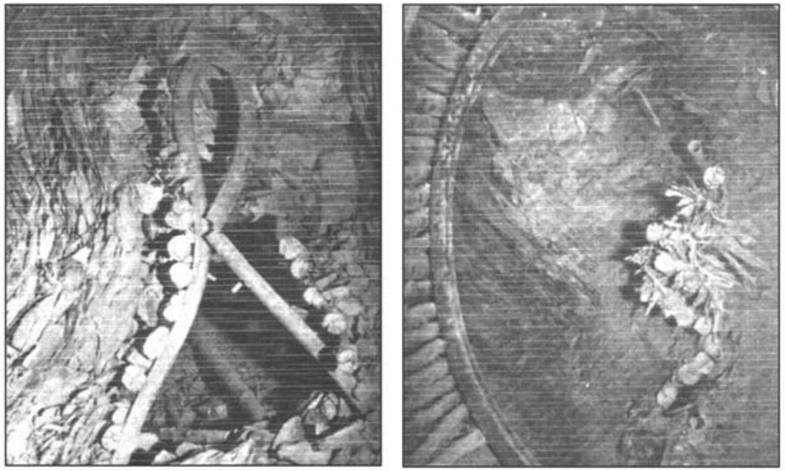
## Underground failures in jointed rocks (cont.)



Effects of a rock burst in a the Kolar gold field, India.
(Courtesy of J.M. Caw, 1956, and Landscape Publishing Ltd, London)



## Underground failures in jointed rocks (cont.)



Effects of a rock burst in the Kolar gold field, India.
(Courtesy of J.M. Caw, 1956, and Landscape Publishing Ltd, London)



## Underground failures in jointed rocks (cont.)

Effects of a rock burst in a South African gold mine

Courtesy of D. Ortlepp, 2003

Effects of an uncontrolled cave in a block caving mine, CO
Courtesy of F. Kendorski, 1976

## Insights into tunnel response to ground shock

The insights will be gained through numerical modeling of loading effects on tunnels inside 3-dimensional rock islands. The rock islands are in a rock mass with several continuous joint sets.

The top boundary of the rock island is loaded by a vertical velocity pulse. The tunnels can be with or without reinforcement or liner.

The modeling is performed by the discrete element method, using the LDEC (Livermore Discrete Element Code) developed by Joe Morris. The various aspects looked into are:

- the effect of joint orientation on tunnel stability
- the effect of joint spacing and block size on tunnel stability
- the effect of using rigid versus deformable rock blocks
- the effect of multiple successive loadings

The results of LDEC calculations are also compared to pictures of actual dynamic tunnel failures.



## Competing factors in the dynamic modeling of tunnels

| Features making the underground facility more resistant to ground shock. | Features making the underground facility less resistant to ground shock |
|---|---|
| Geology | Geology |
| Non-continuous joints | Continuous joints |
| Wider joint spacing | Smaller joint spacing |
| Dilatant joints | Non-dilatant joints |
| Higher shear and tensile strength of the joints | Lower shear and tensile strength of the joints |
| More porous rocks overlying the facility | Less porous rocks overlying the facility |
| Less water saturation of the voids | More water saturation of the voids |
| Facility design | Facility design |
| Smaller span of rock openings | Larger span of rock openings |
| Rock reinforcement | Un-reinforced rock mass |
| Tunnel liner | No tunnel lining |



## A note on joint sets

In this work, rock masses are modeled as transected by continuous (or occasionally discontinuous) joint sets with regular spacing in each set. This is an idealization that gives a somewhat well-behaved connectivity between adjacent rock blocks that is amenable to massively parallel processing (MPP). The true nature of jointing in-situ typically is not precisely known, and real block connectivity could complicate considerably an MPP implementation(see picture).



## Effect of joint orientation

Two basic rock island configurations are used for this part. The islands are 16mx16mx1m, the tunnel is 4-m wide by 5-m high, and the joint spacing is 0.7m

Geology 1; 513 blocks

Geology 2; 519 blocks

## Cases analyzed

**Twenty seven different cases were analyzed corresponding to variations in geology, in joint orientation, in level of loading, and in rock reinforcement.**

**Additional information:**
- **1 MPa all-around stress**
- **Non-dilatant joints**
- **35 degrees friction angle**
- **Joint tensile strength and cohesion = 0.05MPa**

| Case | Geol. | Bolts | Stress (MPa) | Displ. (cm) |
|---|---|---|---|---|
| A070c1a | 1 | No | 0 | 0 |
| A070c2 | 1a | No | 0 | 0 |
| A080c1 | 1 | Yes | 0 | 0 |
| B070c1 | 1 | No | 3 | 1.4 |
| B071c1 | 3 | No | 3 | 1.4 |
| B072c1a | 5 | No | 3 | 1.4 |
| B073c1a | 7 | No | 3 | 1.4 |
| B074c1 | 9 | No | 3 | 1.4 |
| B080c11a | 1 | Yes | 3 | 1.4 |
| B082c1 | 5 | Yes | 3 | 1.4 |
| C070c1a | 1 | No | 6 | 2.8 |
| C080c1a | 1 | Yes | 6 | 2.8 |
| C090c | 2 | No | 6 | 2.8 |
| D090c | 2 | No | 12 | 5.6 |
| E090c | 2 | No | 18 | 8.4 |
| F090c1 | 2 | No | 24 | 11.2 |
| G090c11 | 2 | No | 30 | 14.0 |
| G090c2 | 2a | No | 30 | 14.0 |
| G091c1a | 4 | No | 30 | 14.0 |
| G092c1a | 6 | No | 30 | 14.0 |
| G093c1a | 8 | No | 30 | 14.0 |
| G094c1a | 10 | No | 30 | 14.0 |
| G101c0 | 4 | Yes | 30 | 14.0 |
| G103c1a | 8 | Yes | 30 | 14.0 |
| G104c | 10 | Yes | 30 | 14.0 |
| H090c1 | 2 | No | 36 | 16.8 |
| I090c1 | 2 | No | 45 | 21.0 |



## Effect of joint orientation

**Tunnel in geology 1 under a 3-MPa pulse**

**Tunnel in geology 2 under a 45-MPa pulse**

**A mere change in joint set orientation changes the “strength” of the tunnel by a factor of at least 15**



## Effect of joint orientation (cont.)

**45-degree dip**

**35-degree dip**

**15-degree dip**

**5-degree dip**

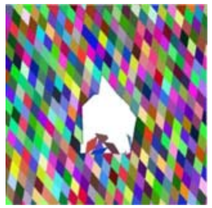
**Tunnel in different variations of geology 1, where the dip angle of joint set 2 is changing and that of joint set 1 is unchanged. Gravity loading only.**



## Effect of joint orientation (cont.)

**20-degree dip**

**30-degree dip**



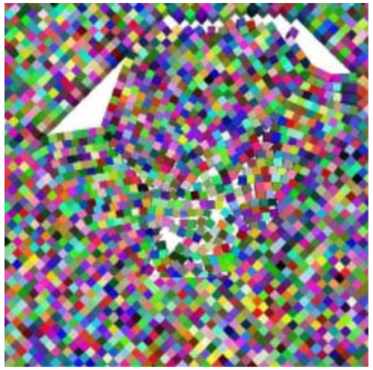
**50-degree dip**

**60-degree dip**

**Tunnel in different variations of geology 2 where the dip angle of joint set 2 is changing and that of joint set 1 is unchanged. Gravity loading only.**

## Effect of joint spacing

Joint spacing 70 cm



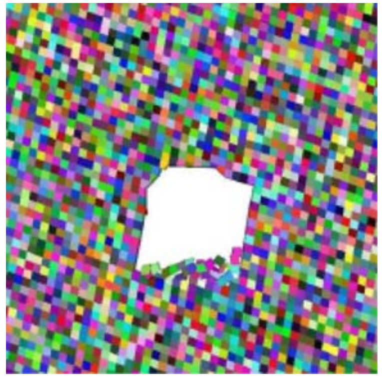
Joint spacing 35 cm

**Tunnel in geology 1, under gravity loading only.**



## Effect of joint spacing

Joint spacing 70 cm



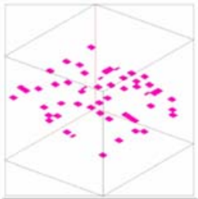
Joint spacing 35 cm

**Tunnel in geology 2 under a 30-MPa pulse.**

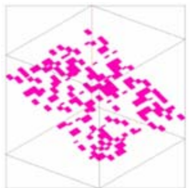


## Effect of joint set continuity or persistence

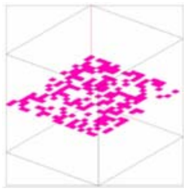
**Joint sets can have any degree of non-persistence. Some examples (after Pariseau, 2005):**



10% persistence

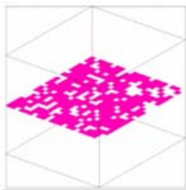


30% persistence



40% persistence

50% persistence

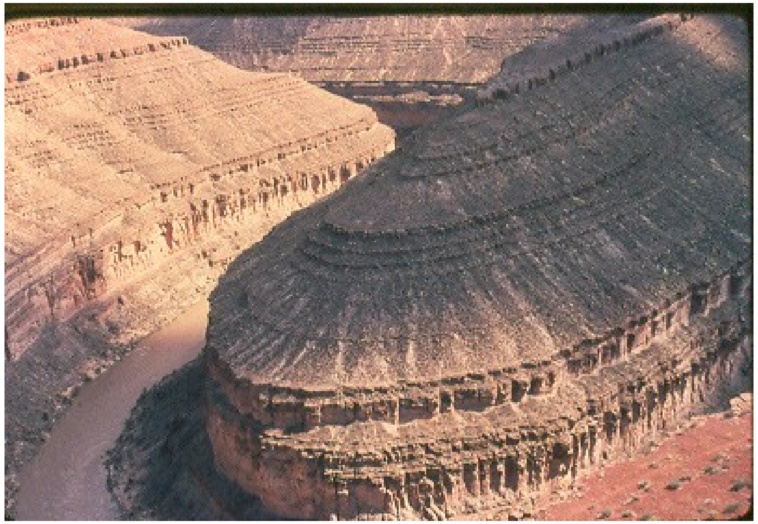


70% persistence

90% persistence



## Persistence of bedding planes



The Goosenecks of the  San Juan river, near Mexican Hat, UT

## Non-persistence of cross-bedding joints

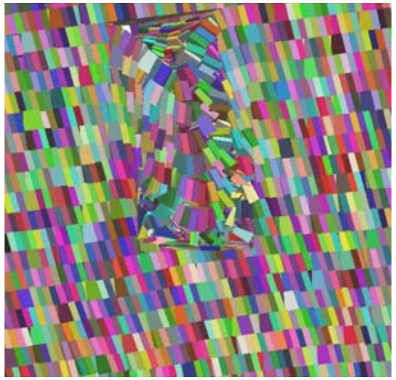
Gypsum quarry at the Ramon crater, Israel (after Hatzor and Feintuch, 2005)



## Effect of joint persistence on unlined tunnels

**All unlined examples are a rock island loaded on the top boundary by a vertical velocity pulse.**

**Geology 1: Steeply dipping bedding (continuous) plus 2 joint sets**



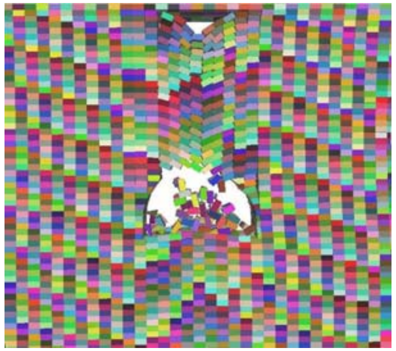
**Continuous joints (10726 blocks)**

**50% persistent joints (8556 blocks)**

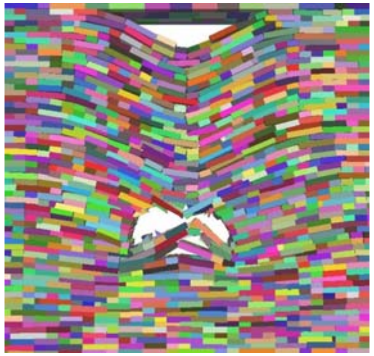


## Effect of joint persistence on unlined tunnels (cont.)

**Geology 2: Horizontal bedding (continuous) plus 2 joint sets**



**Continuous joints (9695 blocks)**

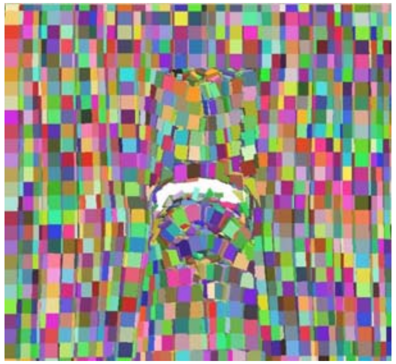


**50% persistent joints (4030 blocks)**



## Effect of joint persistence on unlined tunnels (cont.)

**Geology 3: Horizontal bedding (continuous) plus 5 joint sets, i.e. a very weak rock mass**

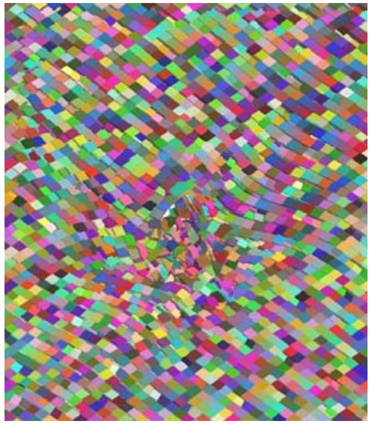


**Continuous joints (11588 blocks)**

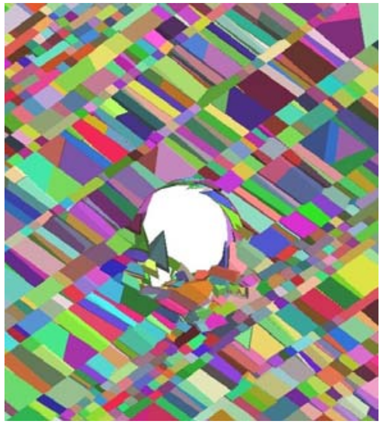
**50% persistent joints (4309 blocks)**

## Effect of joint persistence on unlined tunnels (cont.)

**Geology 4: Three joint sets**



**Continuous joints (12430 blocks)**



**50% persistent joints (2170 blocks)**



## Effect of joint persistence on lined tunnels

**Geology 2: Horizontal bedding (continuous) plus 2 joint sets**

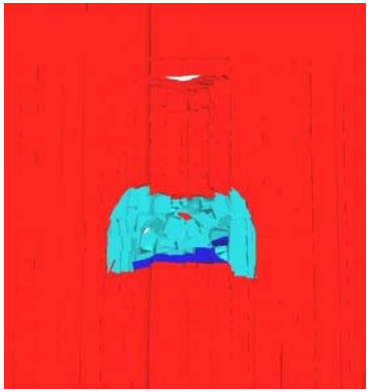
**Continuous joints (9930 blocks)**

**50% persistent joints (4167 blocks)**

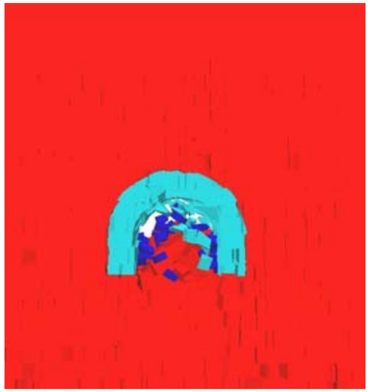


## Effect of joint persistence on lined tunnels

**Geology 3: Horizontal bedding (continuous) plus 5 joint sets. Vertical pulse on top only.**



**Continuous joints (12145 blocks)**



**50% persistent joints (4448 blocks)**



## Effect of joint persistence on lined tunnels

**Geology 3: Horizontal bedding plus 5 joint sets. Normal pulses on top and right boundaries.**

**Continuous joints (12480 blocks)**

**50% persistent joints (4448 blocks)**

## Effect of joint persistence on lined tunnels

**Geology 4: Three joint sets. Normal pulses on top and right boundaries.**

**Continuous joints (13645 blocks)**

**50% persistent joints (2201 blocks)**



## Effect of joint persistence on lined tunnels

**Geology 4: Three joint sets. Normal pulses on top and left and bottom boundaries.**

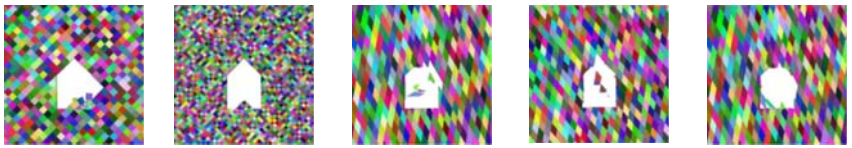
**Continuous joints (13508 blocks)**

**50% persistent joints (2139 blocks)**



## Rigid blocks versus deformable blocks

**Cases with rigid blocks**



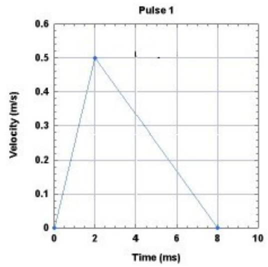
**Cases with deformable blocks**

**Of the 27 cases analyzed, only 5 show a noticeable difference in results between rigid-block and deformable-block analyses. This confirms the preponderant influence of geological discontinuities on tunnel response.**



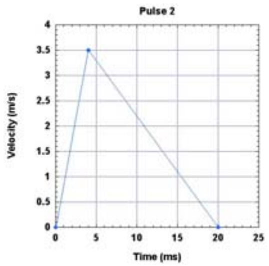
## Effects of successive loadings - example 1

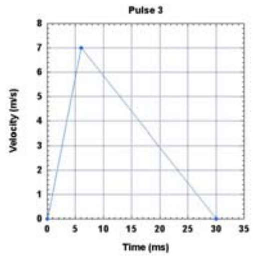
**Rock island of geology 1**




**Up=0.2cm**

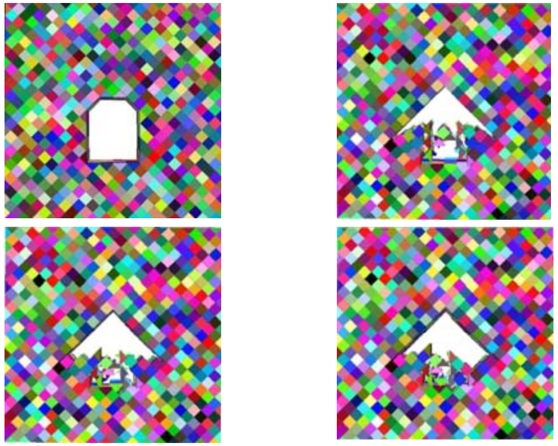
**Up=3.5**




**Up=10.5cm**

## Effects of successive loadings - example 1 (cont.)



Initial state — After pulse1

After pulse 2 — After pulse 3

**After the first ground shock, the tunnel forms a stable arch capable of sustaining even larger successive pulses without additional damage.**

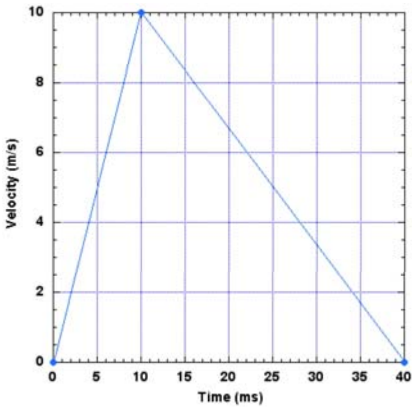


## Examples of stable roof arch

**Arch created by rock fall under ground shock. (chamber in tuff, at the Nevada Test Site)**



## Effects of successive loadings - example 2

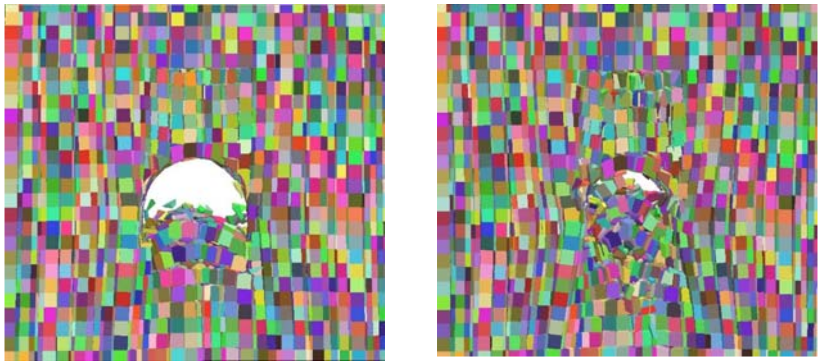



**The rock island is 18m x 2m x 17m. It has 5 joint sets (spacing 60cm) and 11600 rigid blocks. The tunnel is 6-m wide by 4.5-m high.**

**The pulse is applied twice in a row. Its peak displacement is 20cm.**



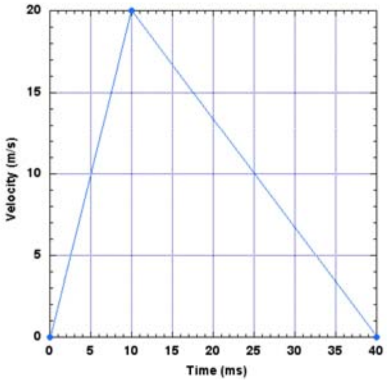
## Effects of successive loadings - example 2 (cont.)



**After the first pulse** — **After the second pulse**

**With this configuration, the repeated loading destroys a tunnel that had withstood the first shock with only modest damage.**

## Effects of successive loadings - example 3

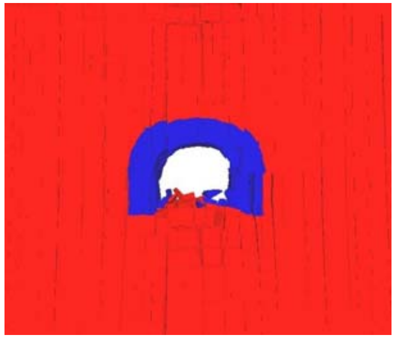



The rock tunnel and the geology are the same as in example 2 , but the tunnel has a 1-m thick reinforced concrete liner.

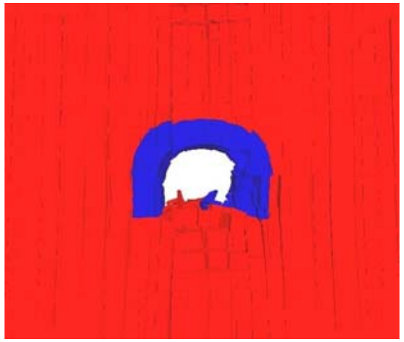
The pulse is stronger than before. Velocity and peak displacement are doubled.



## Effects of successive loadings - example 3 (cont.)



After the first ground shock



After the repeat loading

**In this tunnel, the slightly damaged concrete liner sustains the repeat loading without further damage.**



## LDEC versus actual tunnel failures

Effects of a bump in a coal mine, Belgium.
Courtesy of P.Stassen, 1985.

**The picture shows the buckling of coal-measure rock layers in a Belgian coal mine, due to a coal bump. LDEC can indicate such a rock mass failure mode, as shown in a previous slide.**



## LDEC versus actual tunnel failures (cont.)

Courtesy of D. Ortlepp, 2003.

**The picture shows the failure of a drift in a South African gold mine, due to a rock burst. In a previous slide, LDEC indicated such a fairly symmetrical failure mode as controlled by the joint pattern.**

## LDEC versus actual tunnel failures (cont.)

Courtesy of D. Ortlepp, 2003.

**The picture shows an asymmetrical roof failure due to a rock burst in a drift in a South African gold mine. In a previous slide, LDEC indicated such a mode of roof failure as controlled by the joint pattern.**



***The 21st century***

***Three-dimensional massively parallel discrete element simulations***



## A glimpse into the future

**The dynamic loading of a complex of multiple drifts and chambers was simulated with the Livermore Discrete Element Code (LDEC) created by Dr. Joseph Morris of LLNL.**

**The underground facility is set within a 60m cube. Its height is 25m and its lateral dimensions are ~ 60m. The crown of the upper chamber is at a depth of 47m.**

**The rock mass has 3 non-persistent joint sets with an average spacing of 30cm. Lateral confinement is 1 MPa.**

**The LDEC model has 8 million polyhedral rock blocks, and about 100 million elements overall (rigid blocks plus deformable contact elements).**

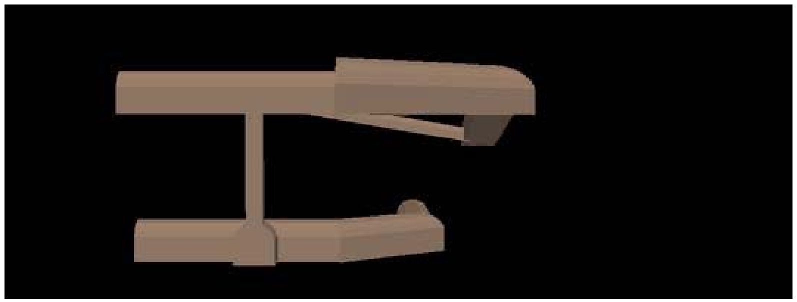
**The loading pulse imparts a velocity-time history near the crown of the upper chamber that has a rise-time of 1ms, a peak of 4m/s, and a decay time of 19ms. The resulting peak displacement is 8cm.**

**Boundaries not loaded by the pulse are non-reflecting.**

**The simulation ran on 3840 parallel processors for about 4 days ($42^{+}$ CPU years)**



## A glimpse into the future (cont.)



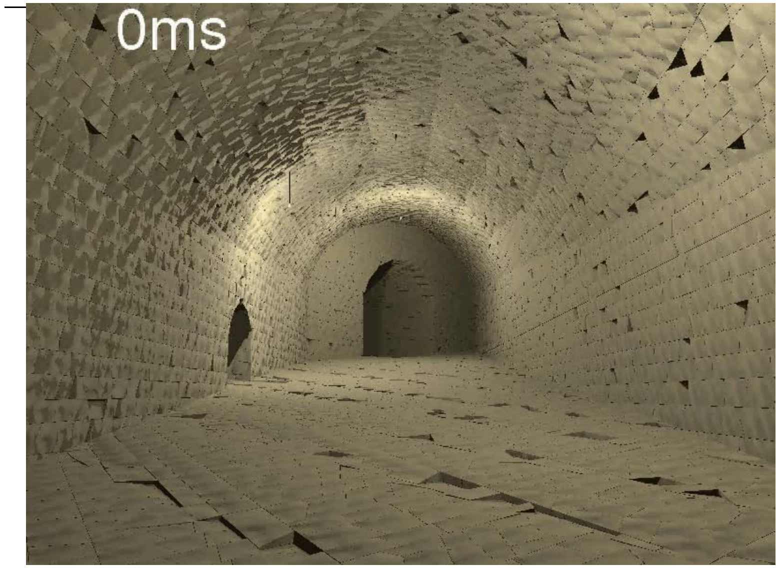
**The ground shock effects will be observed from inside the upper chamber on the chamber itself and on the small drift, as well as from inside the drift.**

## A glimpse into the future (cont.)

Geologic structure in the simulation domain, resulting from non-continuous joint sets

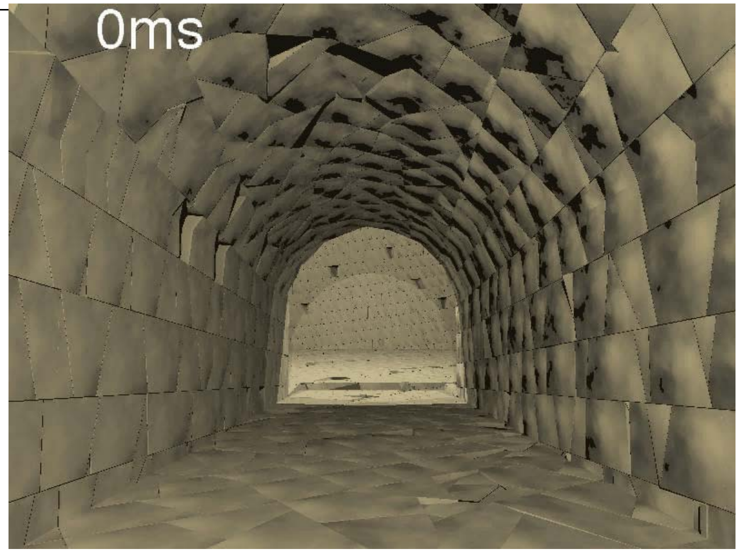


## View from inside the upper chamber




## Viewing the small drift from inside the chamber


## Viewing the small drift from inside the itself



## Viewing the lower level




## Viewing the lower level (cont.)


## Summary and conclusions

The orientation of geological discontinuities is a major controlling factor in tunnel stability. An example was shown where the mere change of orientation of one joint set increased tunnel "strength" by a factor of 15.

We have re-affirmed that joint spacing, or the ratio of mean block size to mean tunnel dimension, is also a very influential parameter of tunnel "strength".

Joint persistence was shown to be an influential factor in tunnel strength, but more joint set continuity does not always imply lower tunnel hardness.

It was demonstrated that rigid block models with deformable block interfaces are adequate to represent the dynamics of many jointed rock masses when the strength of the intact rock blocks is not exceeded.



## Summary and conclusions (cont.)

In the case of repeated loading of tunnels, several simulations indicated that successive loadings may or may not result in additional damage. It can happen that a tunnel will reach a stable configuration after initial damage, and that damaged tunnels may withstand subsequent loadings without further failure.

Comparisons of LDEC simulations with records of actual tunnel failures show that discrete element models are very powerful and very realistic tools to investigate the response of structures in jointed rocks.

A very large simulation performed with LDEC shows that the state-of-the-art is coming much closer to providing realistic representations of real-life complex structures in rocks under dynamic loading.

Simply stated, when one tries to assess the damage created by shock waves on underground structures:
- the knowledge of the subsurface geology is of critical importance, and
- the uncertainties in effects estimates can be very significant.