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INSIGHTS INTO THE DYNAMIC RESPONSE OF TUNNELS IN JOINTED ROCKS

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INSIGHTS INTO THE DYNAMIC RESPONSE OF TUNNELS IN JOINTED ROCKS

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Abstract

Tunnels in jointed rocks can be subjected to severe dynamic loads because of rock bursts, coal bumps, and large earthquakes. A series of 3-dimensional simulations was performed, based on discrete element analysis to gain insights into the parameters that influence the response of such tunnels.
The simulations looked at the effect of joint set orientation, the effect of joint spacing, the effect of peak displacement for a given peak velocity, the effect of pulse peak velocity for a given displacement, the influence of using rigid versus deformable blocks in the analyses, and the effect of repeated loading.
The results of this modeling were also compared to field evidence of dynamic tunnel failures. This comparison reinforced the notion that 3-dimensional discrete element analysis can capture very well the kinematics of structures in jointed rocks under dynamic loading.
The paper concludes with a glimpse into the future. Results are shown for a 3-dimensional discrete element massively parallel simulation with 100 million contact elements, performed with the LLNL LDEC code

Overview

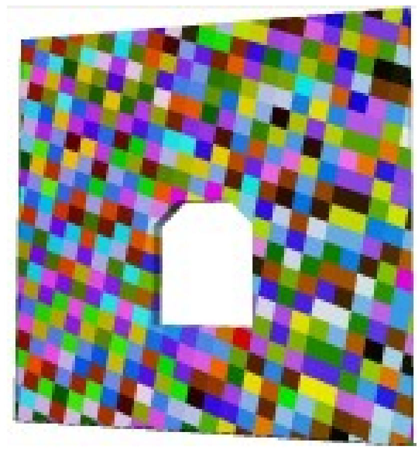
Multiple tunnel-in-rock-island simulations were performed with the LDEC 3-dimensional discrete element code [1] to examine several issues concerning estimates of tunnel stability:

1. The influence of joint set orientation
2. The influence of joint spacing
3. The effect of using rigid versus deformable blocks in LDEC
4. The influence of peak displacement for a given pulse peak velocity
5. The influence of peak velocity for a given peak displacement,
6. The effect of multiple loadings

The results of some of these calculations turned out to be strikingly similar to pictures from actual tunnel failures. This highlights the adequacy of LDEC models to represent the kinematics of real rock masses and real tunnels.
The paper concludes with a glimpse into the future. Results are shown for a 3-dimensional discrete-element, massively-parallel simulation with 100 million contact elements, performed with the LLNL LDEC code

The first three issues were examined using the two basic rock-island configurations shown in Figure 1. The rock island is 16mx16mx1m. The tunnel is 4-m wide by 5-m high. The rock joint spacing is 0.7m in the plane of the figure and there is one block in the thickness of the island. The simulations were performed in plane strain. Twenty-seven different cases were calculated, corresponding to variations in geology, in joint orientation, in level of loading, and in rock bolting (Figure 2). Table 1 summarizes the attributes of the 27 cases.

Geology 1 (513 blocks)



Geology 2 (519 blocks)

Figure 1. Basic joint geometries for the first three series of LDEC simulations (27 calculations)

Table 1. Summary of the Main Features for the 27 Simulations

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

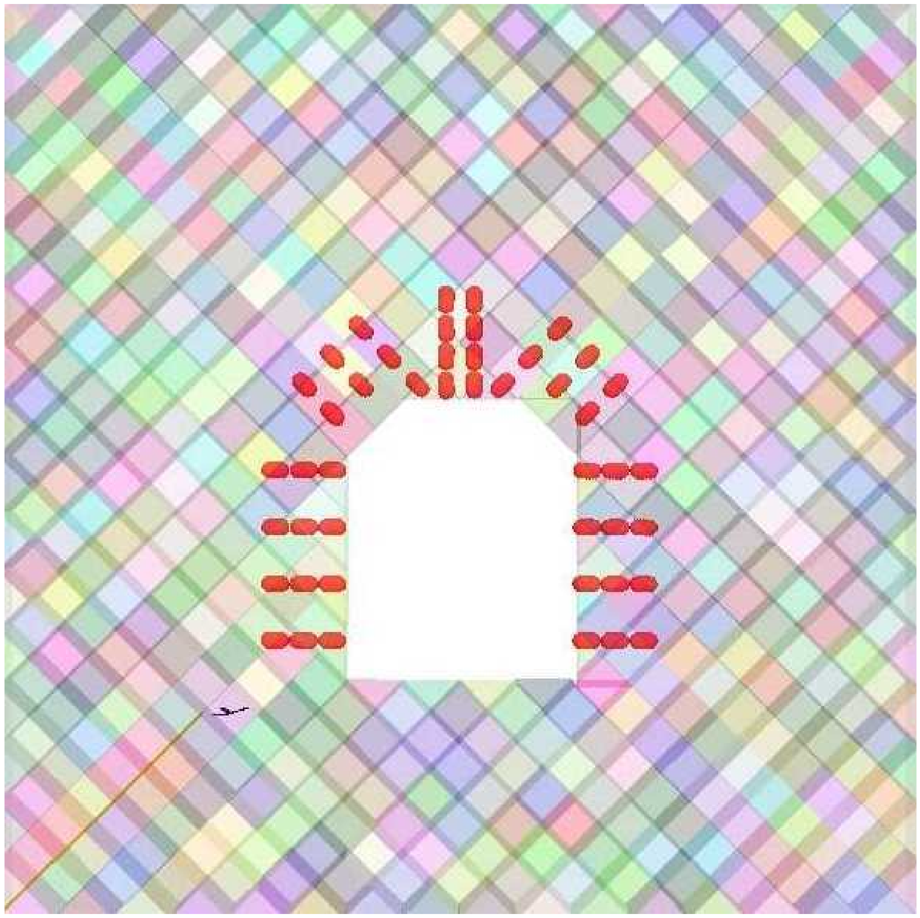
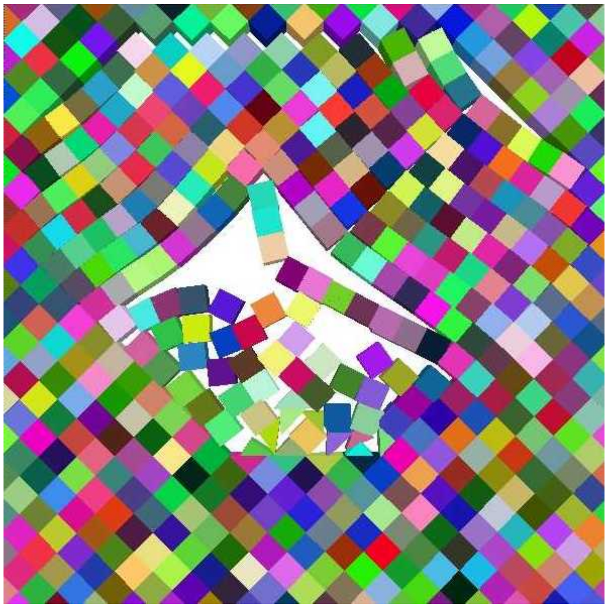


Figure 2. Rock Bolt Pattern for Reinforced Tunnels

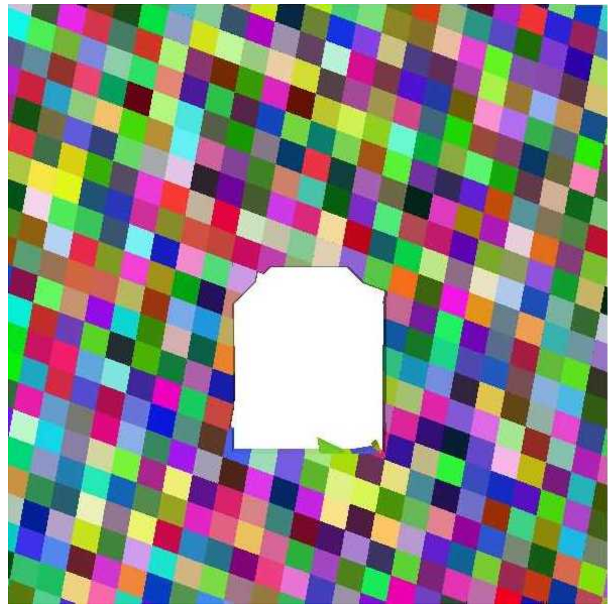
The odd-numbered geologies are variations on geology 1, and the even-numbered are variations on geology 2. Cases A were under gravity loading only. For case B through I, loading was under the form of a triangular velocity pulse applied at 45^o to the top and left boundaries of the rock island. The rise time and decay times were 4 ms and 16 ms respectively for cases B through F, and 5 ms and 20 ms respectively for cases G through I. The peak displacement created by the velocity pulse is shown in Table 1, as well as the corresponding peak stress. The island was put under a 2MPa uniform all-around static pressure. The tunnel was excavated under that initial stress at 50ms, and the pulse was applied to the boundaries at 100ms. After this, the simulations were run until the rock island reached a steady state.

Effect of Joint Orientation on Tunnel Hardness

A first comparison was made for the same tunnels in geologies 1 and 2 (Figure 3). It is shown that joint system orientation alone can have a considerable effect on tunnel hardness. With the same number of joint sets, the same joint spacing, the same rock material properties, the same joints properties, the same in-situ stresses, and the same tunnel geometry, the tunnel hardness in geology 2 is over 15 times that of its hardness in geology 1.



a) Tunnel in geology 1, under a 3-MPa pulse



b) Tunnel in geology 2, under a 45-MPa pulse

Figure 3

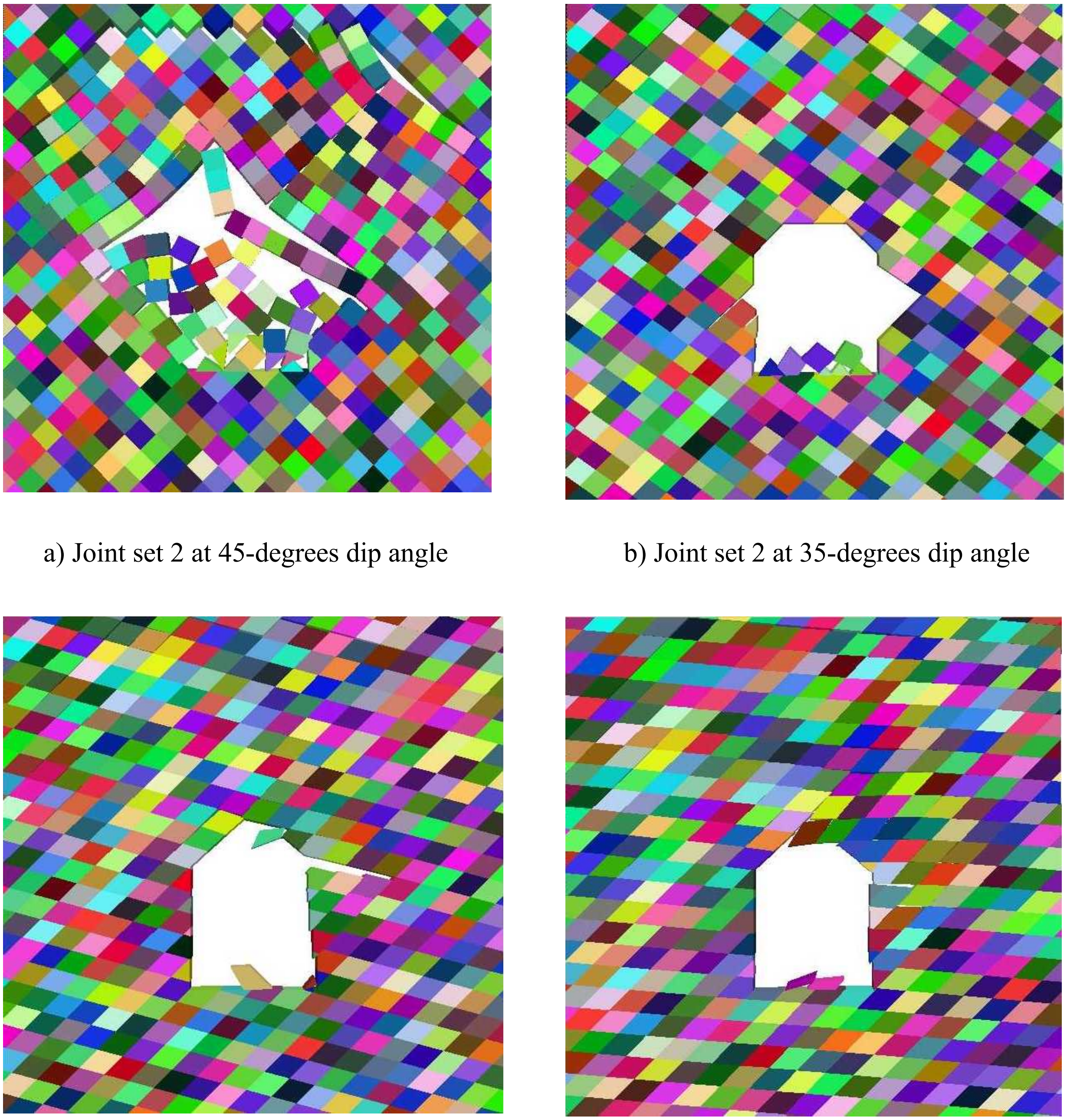
The effect of joint orientation was further examined by varying the dip angle of a single joint set in geologies 1 and 2, under gravity loading only. Figure 4 shows the results for variations from geology 1, and Figure 5 from geology 2. For these two geologies, the tunnel stability is greatly enhanced when joint dip angle is reduced. This is a common observation made underground, in jointed rock formations.

Effect of Joint Spacing on Tunnel Hardness

Two comparisons are shown in Figure 6 for cases where the joint spacing has been reduced from 70cm to 35cm in geologies 1 and 2. As known experimentally, closer joint spacing can dramatically decrease tunnel stability.

Comparison of Rigid-Block and Deformable-Block LDEC Results

Because deformable-block simulations can take several times the computing time of rigid-block calculations, since they require a shorter time-step for numerical stability, there is motivation in modeling with rigid blocks if possible. The interfaces between the blocks are always deformable, with specified shear and normal stiffness. The 27 cases of Table 1 were run with rigid blocks and with deformable blocks. In 22 cases the tunnel response was identical. In 2 cases damage was higher in the deformable-block model, and in 3 cases in the rigid-block model. Results of these 5 cases are compared in Figure 7. It is concluded that there does not seem to be a systematic difference between the two approaches, and that the results are generally equivalent. This highlights the fact that geological discontinuities exert a controlling influence on the response of jointed hard rock masses. Thus, in such media rigid-block calculations will generally be preferred since they are much faster than those with deformable blocks, while appropriately representing the kinematics of those media.



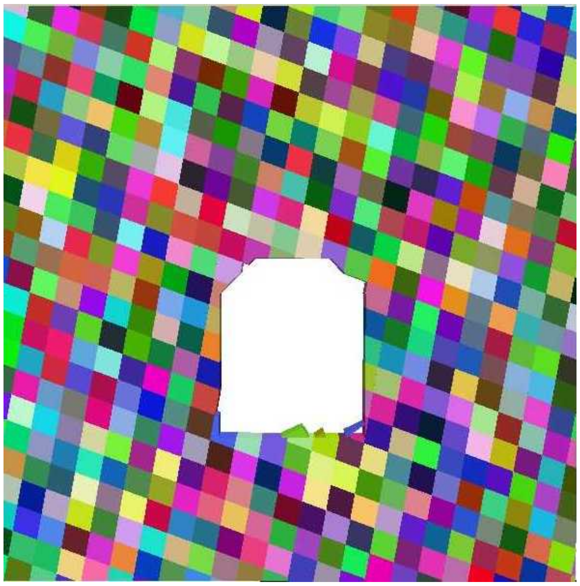
a) Joint set 2 at 45-degrees dip angle

b) Joint set 2 at 35-degrees dip angle

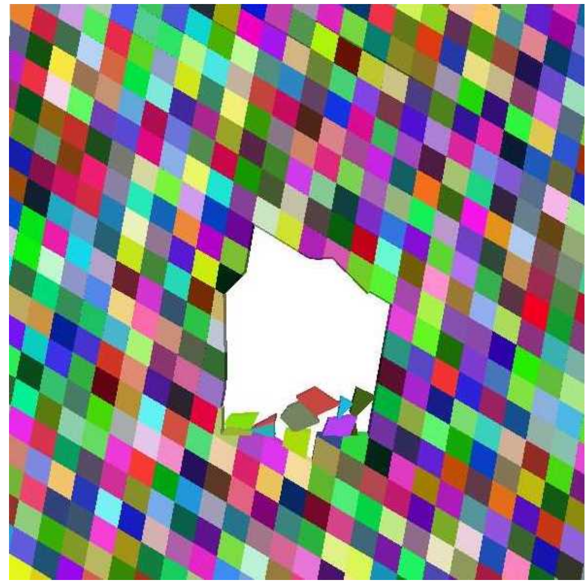
c) Joint set 2 at 15-degrees dip angle

d) Joint set 2 at 5-degrees dip angle

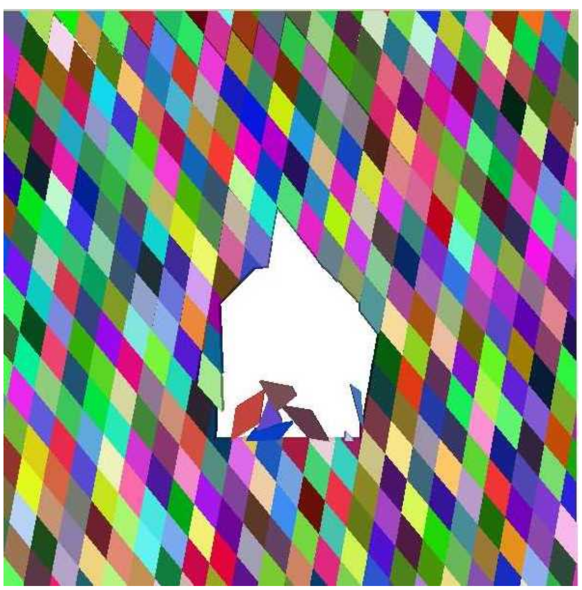
Figure 4. Tunnel in different variations of geology 1; gravity loading only.



a) Joint set 2 at 20-degrees dip angle



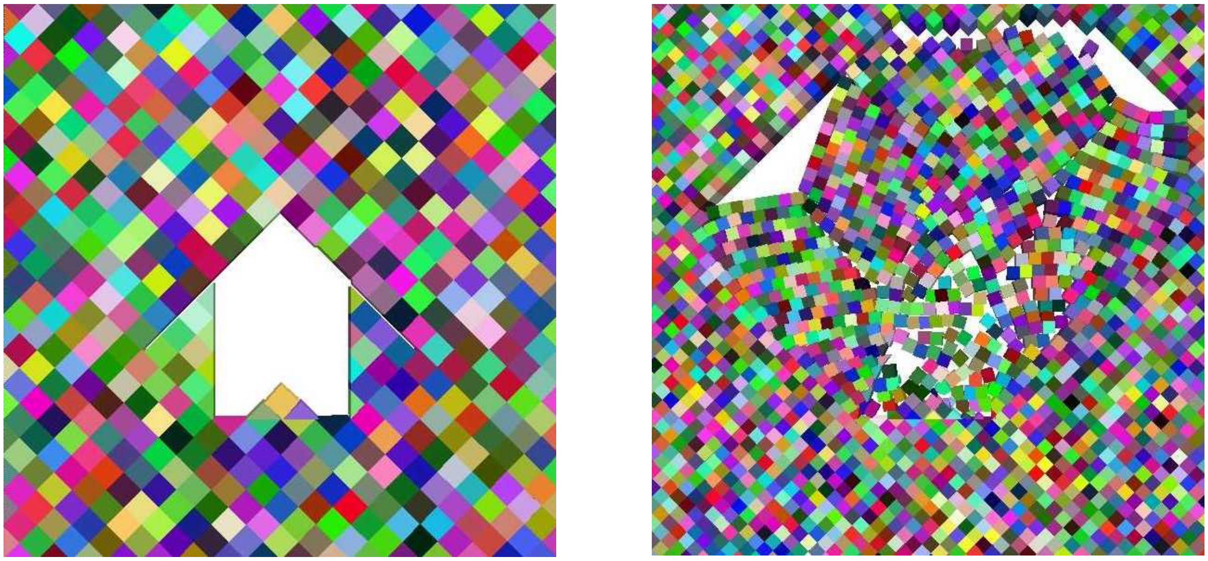
b) Joint set 2 at 30-degrees dip angle



c) Joint set 2 at 50-degrees dip angle

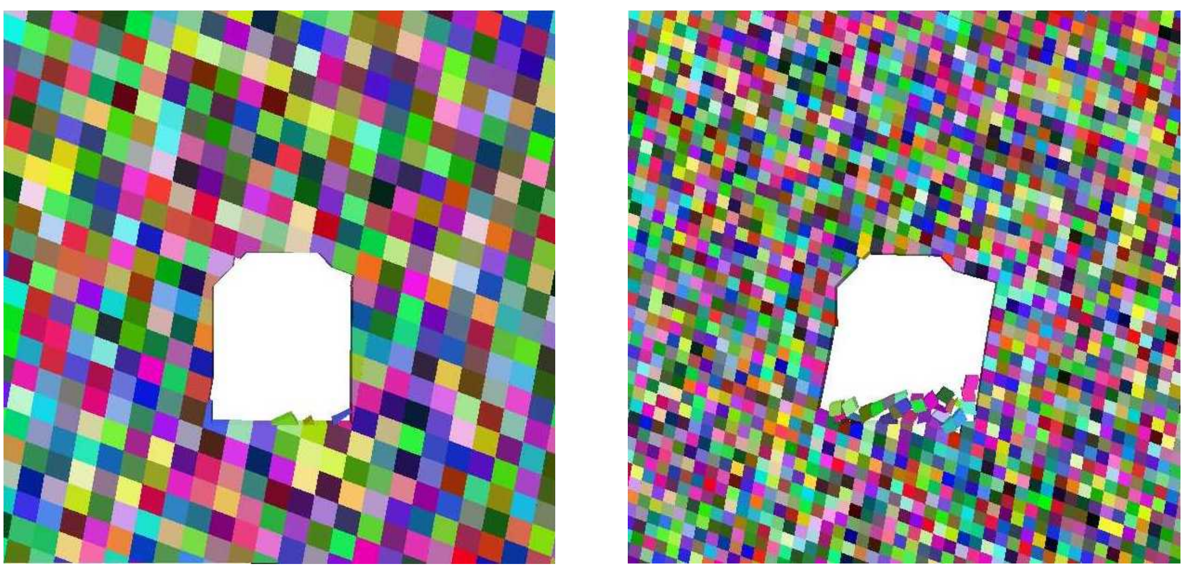
d) Joint set 2 at 60-degrees dip angle

Figure 5. Tunnel in different variations of geology 2; gravity loading only



Joint spacing 70cm   Joint spacing 35cm

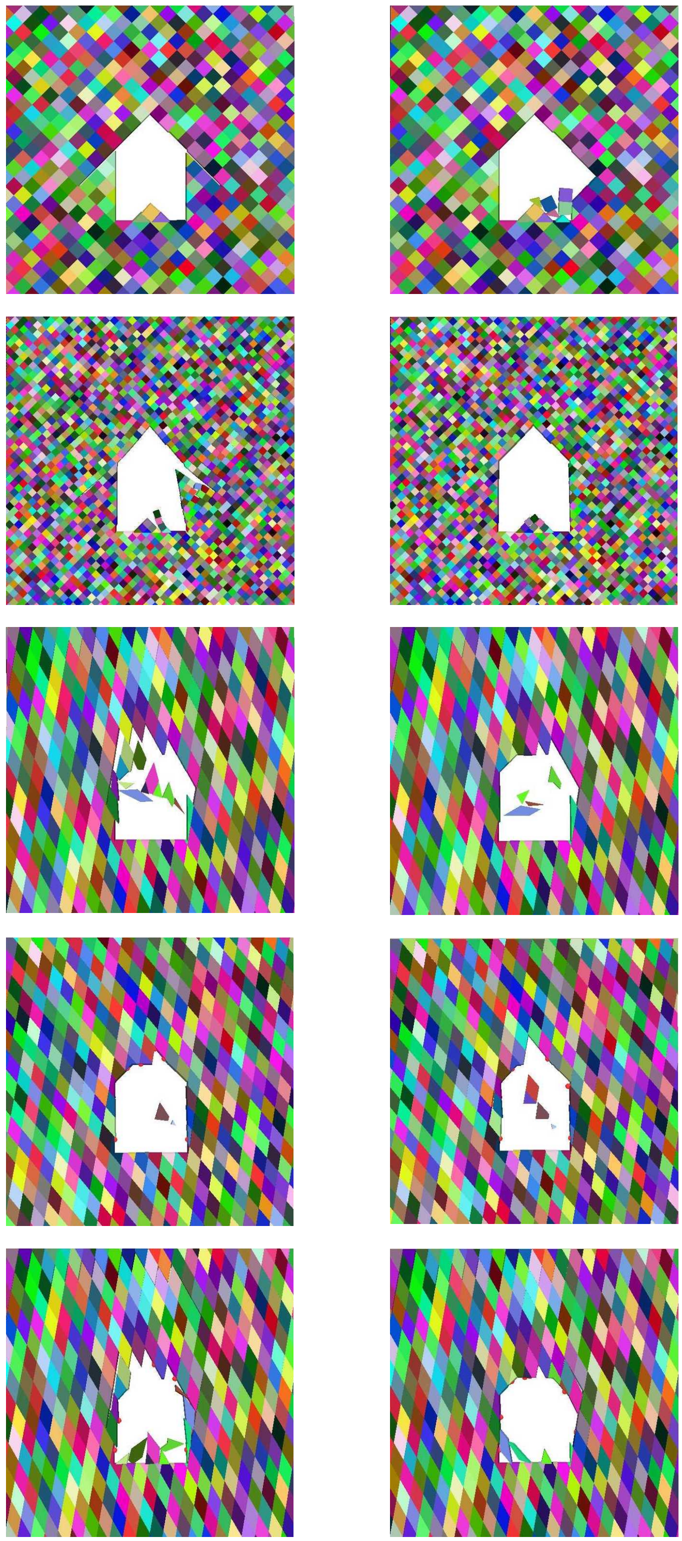
a) Tunnel in geology 1 under gravity loading



Joint spacing 70cm   Joint spacing 35cm

b) Tunnel in geology 2 under 30-MPa pulse

Figure 6. Effect of Joint Spacing on Tunnel Stability



a) Case A070-1. Geology 1.
Joint spacing 70cm.
No pulse

b) Case A070-2. Geology 1.
Joint spacing 35cm
No pulse

c) Case G094. Geology 10.
30-MPa pulse

d) Case G103. Geology 8.
30-MPa pulse

e) Case G104. Geology 10.
30-MPa pulse

Figure 7. Cases where there is a difference between LDEC results with rigid blocks (left column) and deformable blocks (right column).

Effect of Peak Displacement for a Given Peak Velocity

The peak velocity of a pulse, v_p, can be used to estimate the free-field peak stress as $\sigma = \rho.c.v_p$, where c is the P-wave velocity through the medium. Then, that stress can be used as a metric of tunnel strength. But, this may be a crude simplification because it ignores the pulse duration and hence the displacement due to that pulse. A series of calculations loaded the tunnel in the rock island shown below, with a 5m/s peak velocity pulse and various durations and peak displacements, also shown in Figure 8. The island has 10600 blocks. There are three joint sets: one steeply dipping with a spacing of 12cm, one vertical with a spacing of 50cm, and one sub-horizontal with a spacing of 50cm as well. The rock blocks are rigid. The effects are shown in Figure 9. For the same peak velocity, corresponding to the same peak free-field stress, damage tends to increase with peak displacement. The simulations typically were carried out to 3000ms.

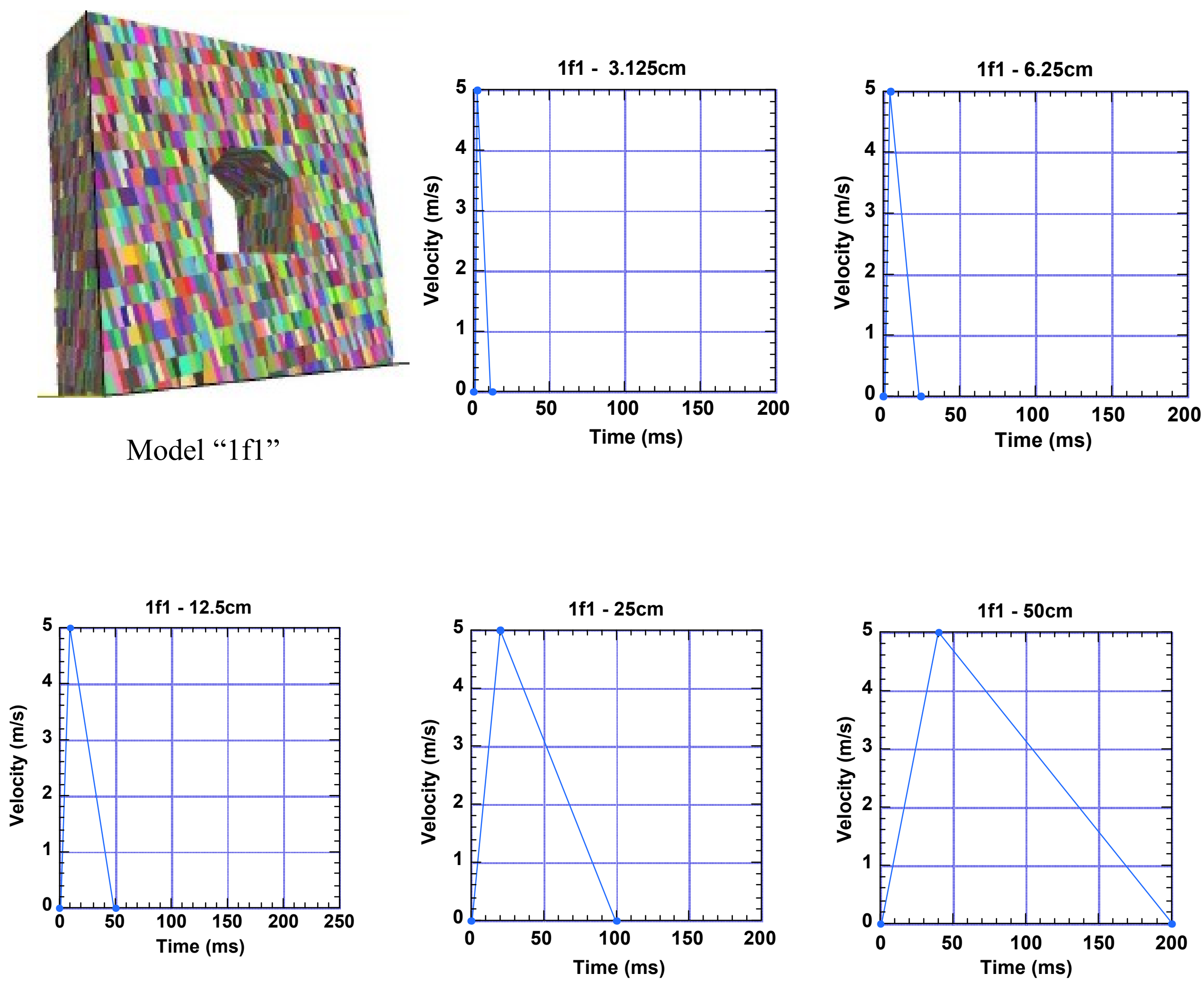
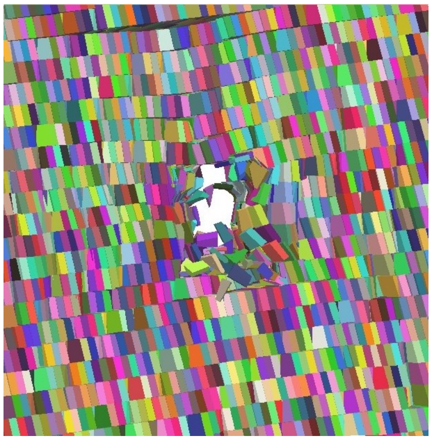
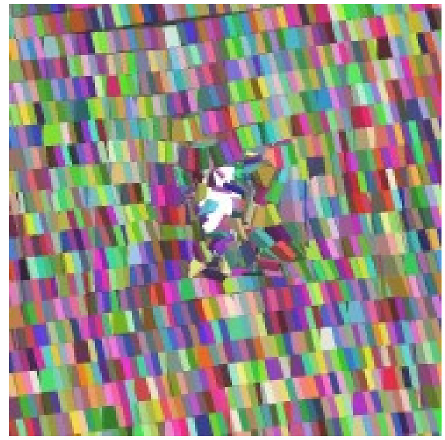


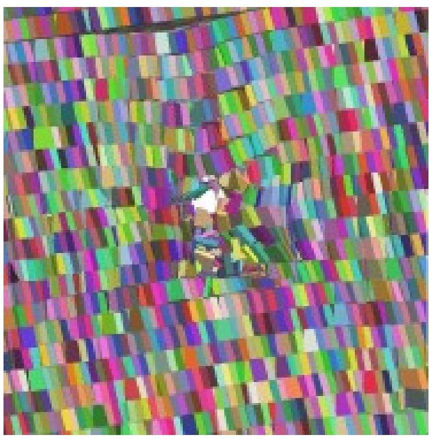
Figure 8. Rock island and pulses with 5m/s peak velocity and various durations/peak displacements



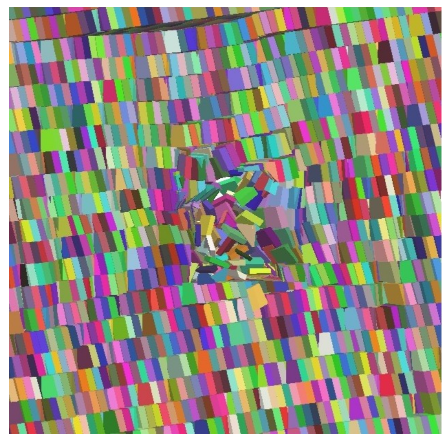
a) Displacement 3.125cm



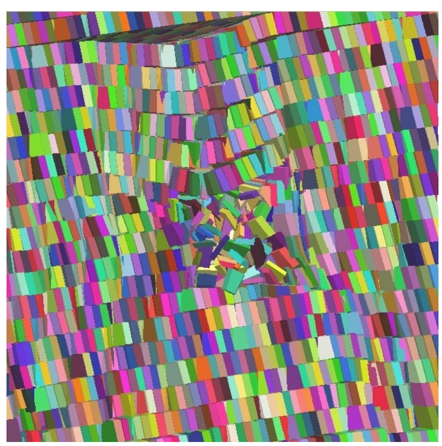
b) Displacement 6.25cm



c) Displacement 12.5cm



d) Displacement 25cm



e) Displacement 50cm

Figure 9. Effects of pulses with the same peak velocity and different duration/peak displacement.

Effect of Peak Velocity for a Given Total Displacement

The stability of a tunnel may be related to the total displacement due to the ground shock, compared to the mean joint spacing. In that case, the effect on the tunnel would be independent of the shape of the velocity pulse that creates such a total displacement. To test that hypothesis, a series of calculations was run on the rock island of Figure 8 for a displacement of 12.5cm. The pulses are shown in Figure 10; the peak velocity varies between 1 and 20m/s and the duration is between 250 and 12.5ms. Results are shown in Figure 11. The hypothesis is not validated.
The inference from the above two series of simulations is that both peak velocity and pulse duration must be accounted for in estimating damage on a tunnel in jointed rocks.

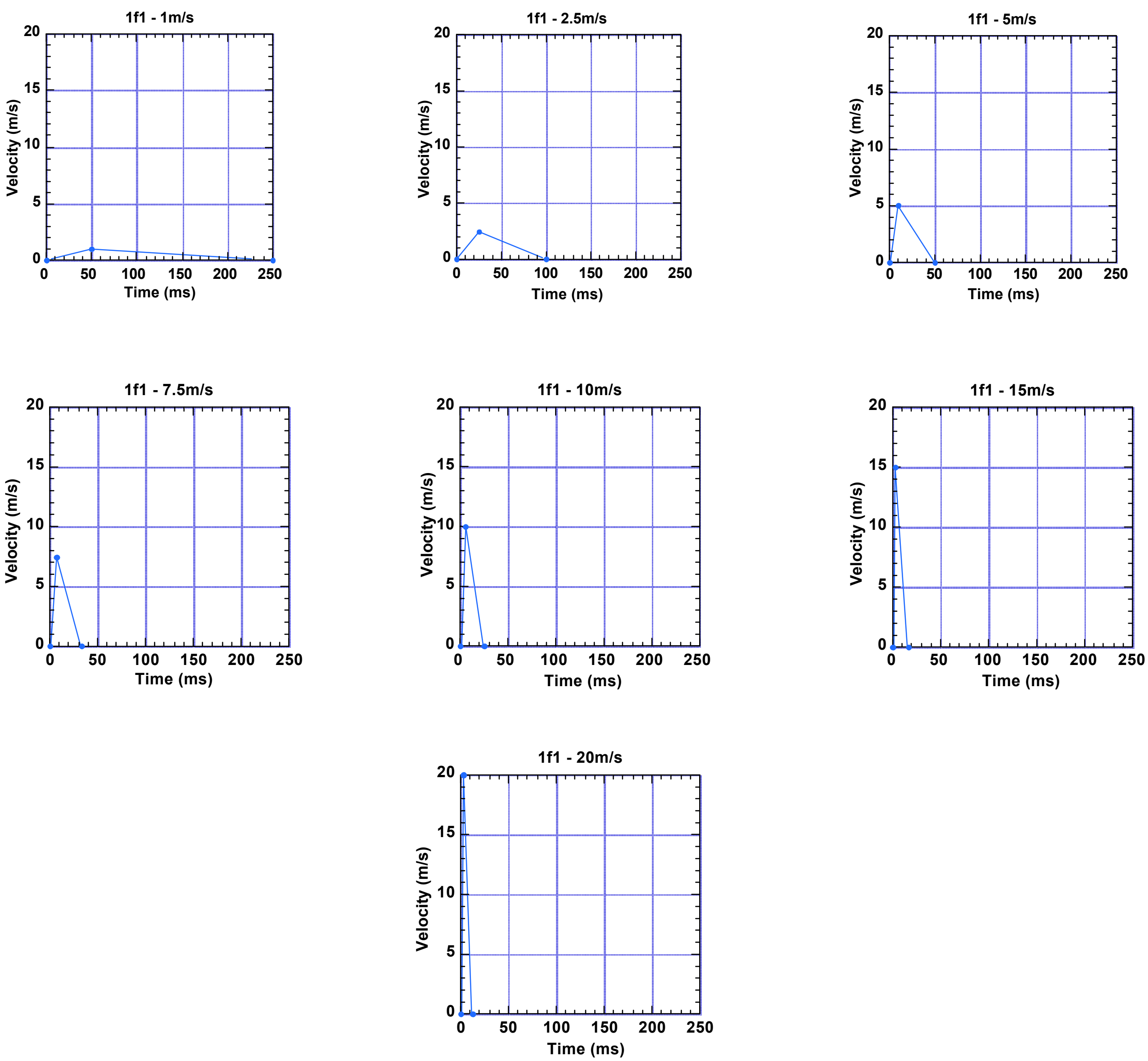


Figure 10: Various velocity pulses, all producing a total displacement of 12.5 cm

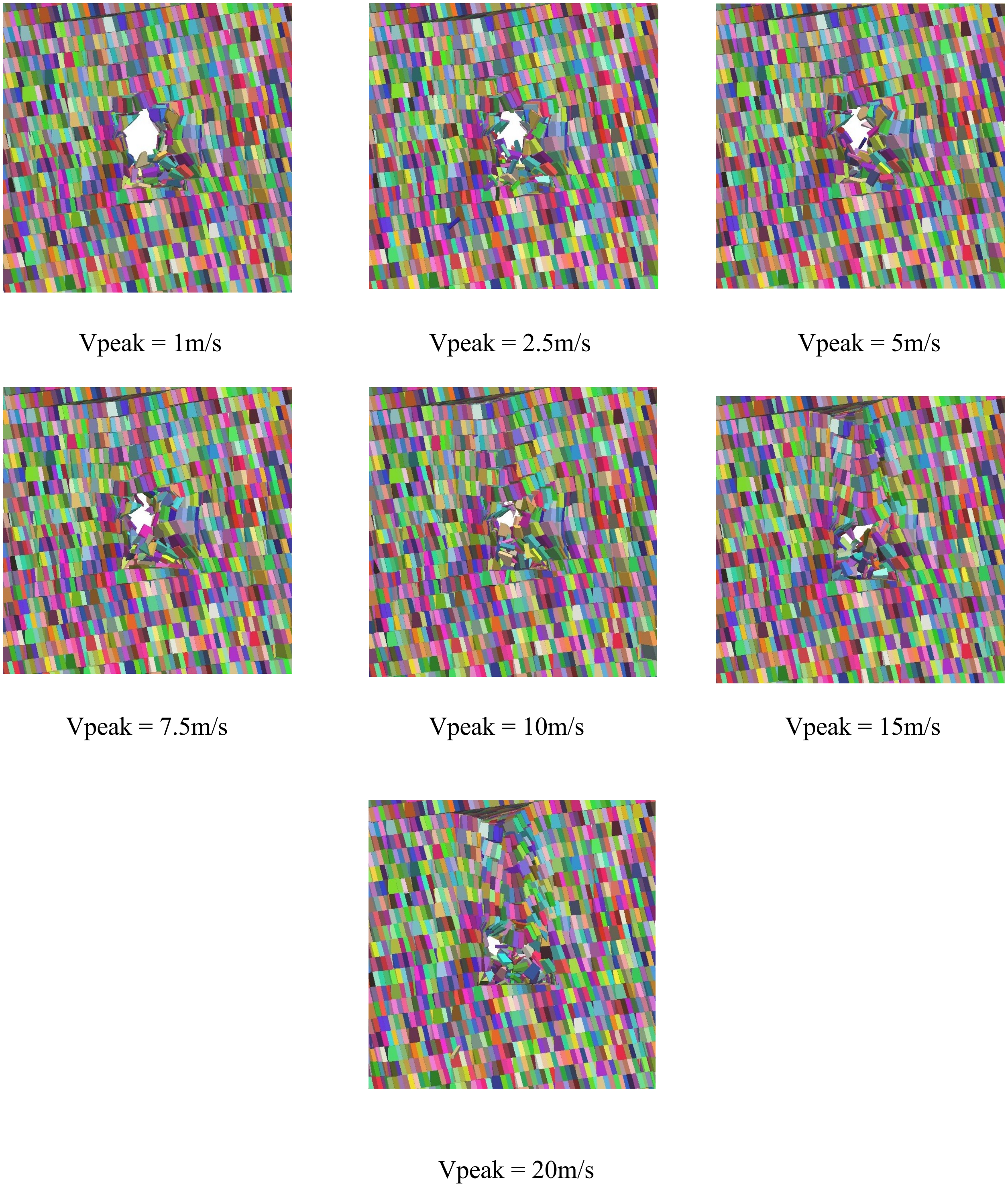
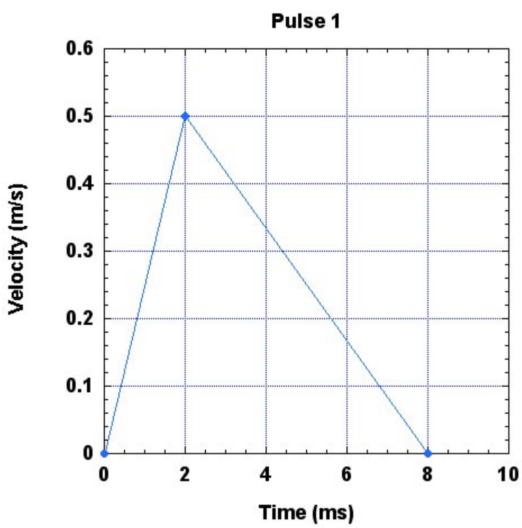


Figure 11. Effect of pulses with the same peak displacement and various peak velocities

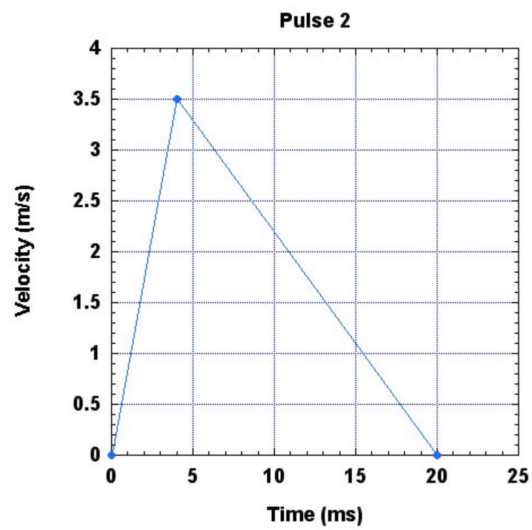
Repeated Loading of Tunnels

It could be presumed that repeated loadings will progressively weaken a tunnel, because of the dislocations of rock blocks that are created with each loading. To test that assumption several simulations were performed with various configurations.

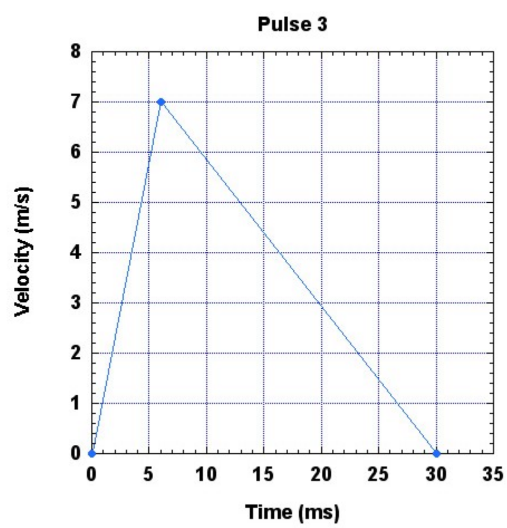
The first example uses geology 1 of Figure 1. The rock mass is not reinforced, the joint spacing is 70cm in the plane of the figure, and the island is under a 1 MPa all-around stress. The three vertical load pulses shown in Figure 10 were applied sequentially at the top of the rock island, and the effects are shown in Figure 11. The small initial pulse is able to destabilize the roof of the tunnel, but then a much more stable shape is obtained that is not affected by the following larger pulses. So, the above premise is not verified in this case.



a) Peak displacement = 0.2cm

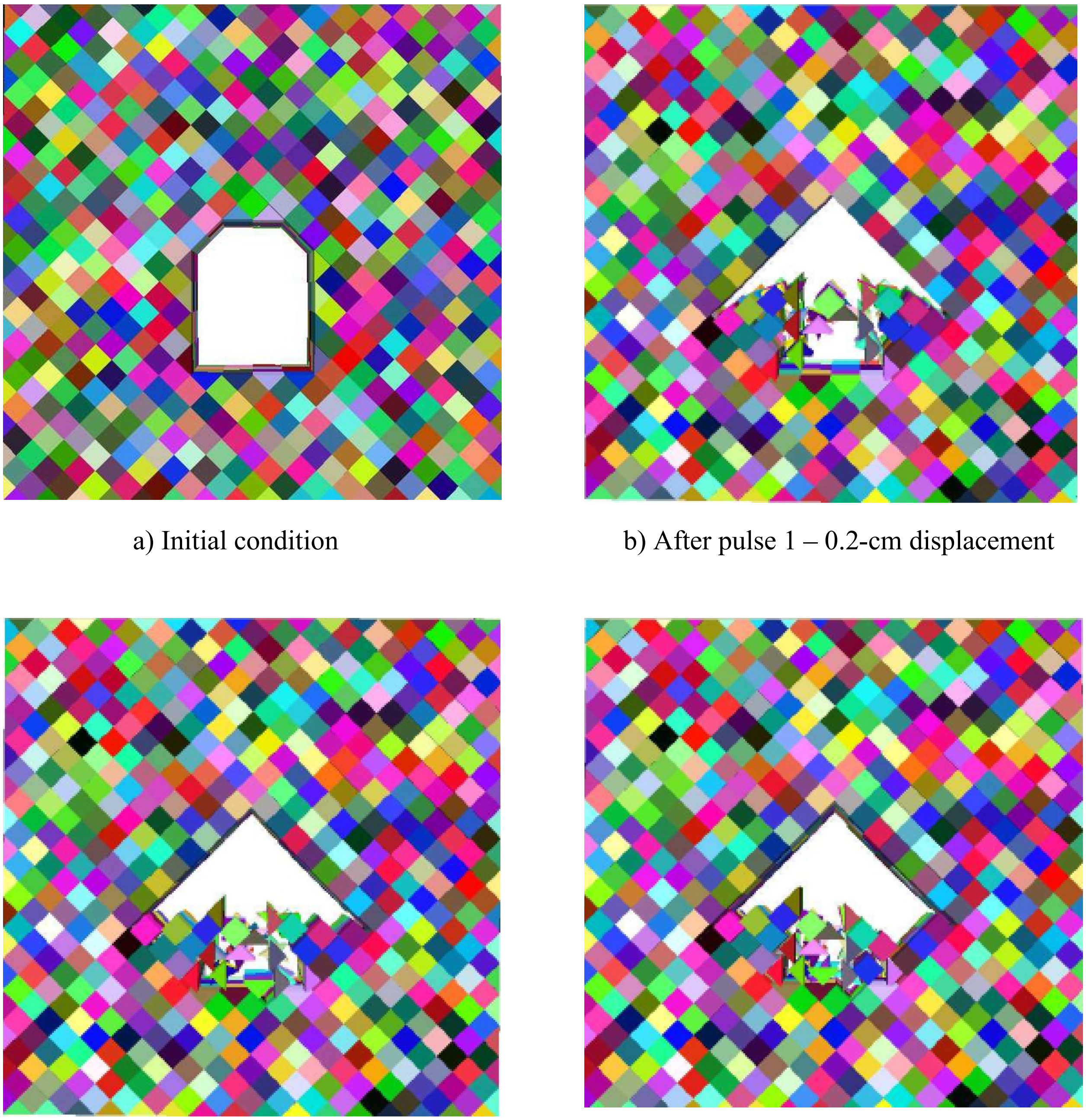


b) Peak displacement = 3.5cm



c) Peak displacement = 10.5cm

Figure 12. Successive vertical velocity pulses applied to the top of the rock island in geology 1. Note that the total displacement in each case will be the sum of the displacement of successive pulses.



a) Initial condition

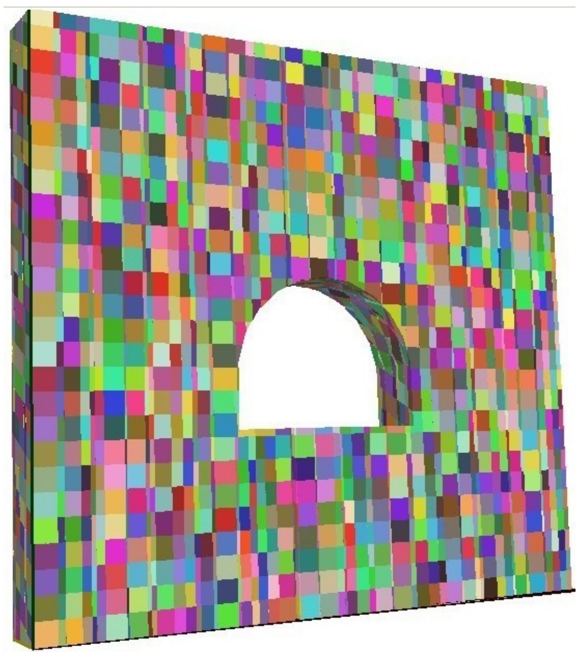
b) After pulse 1 – 0.2-cm displacement

c) After pulse 2 – 3.7-cm displacement

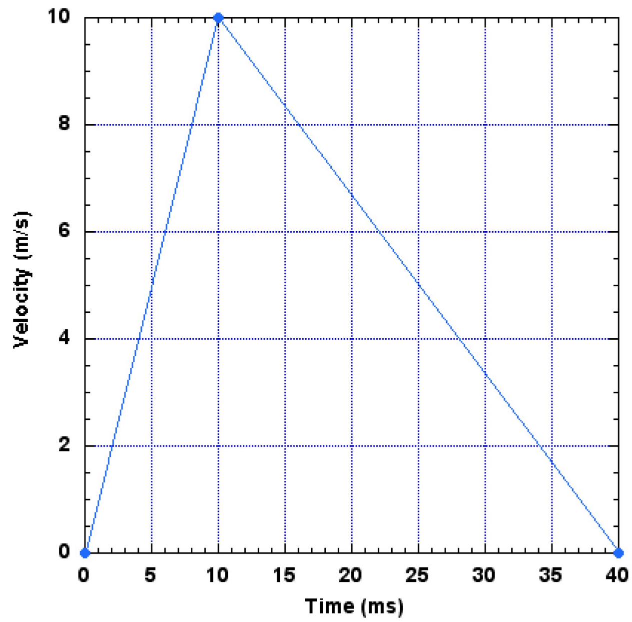
d) After pulse 3 – 14.2-cm displacement

Figure 13

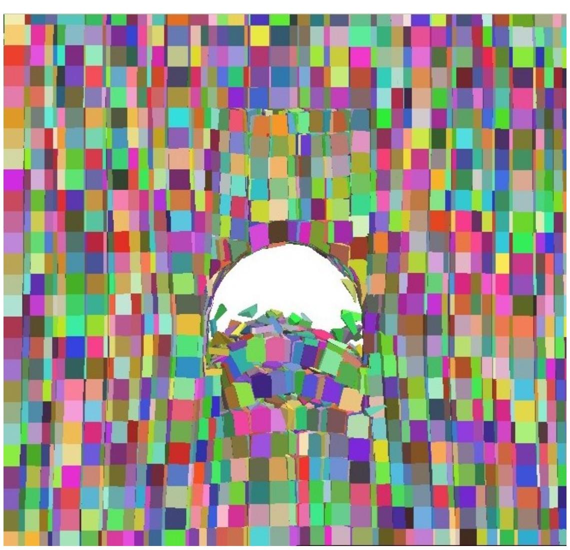
The next repeat loading case is with the configuration shown in Figure 14a. The rock mass has five joint sets all with spacing of 60cm, the tunnel is 6-m wide by 4.5-m high, and the island has 11600 rigid blocks with deformable joints. The velocity pulse is shown in Figure 14b. It gives a total displacement of 20cm. In this case, the conditions after the first and repeat loadings shown in Figures 14c and 14d indicate much more damage to the tunnel after reloading.



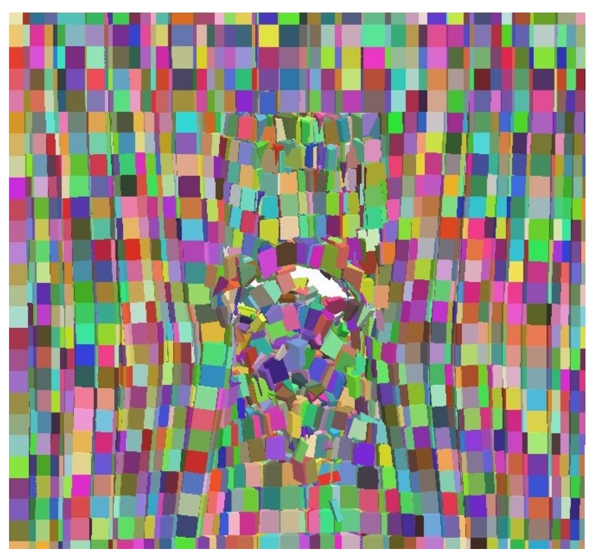
a) Initial condition



b) Applied velocity pulse



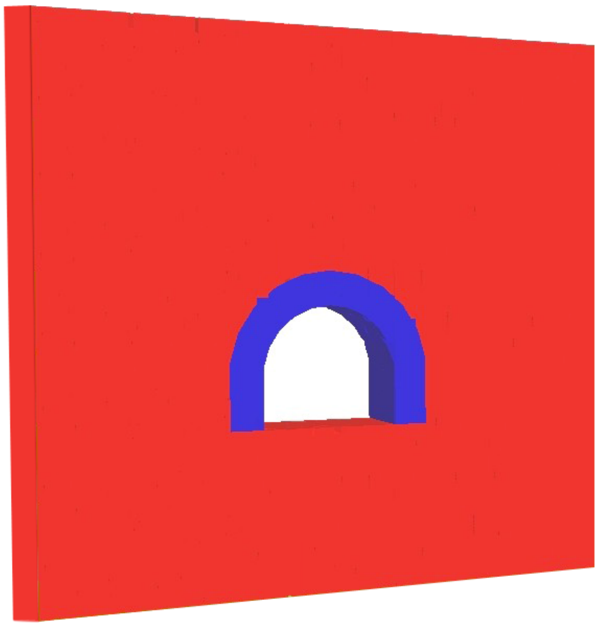
c) after the first loading; 20-cm displacement



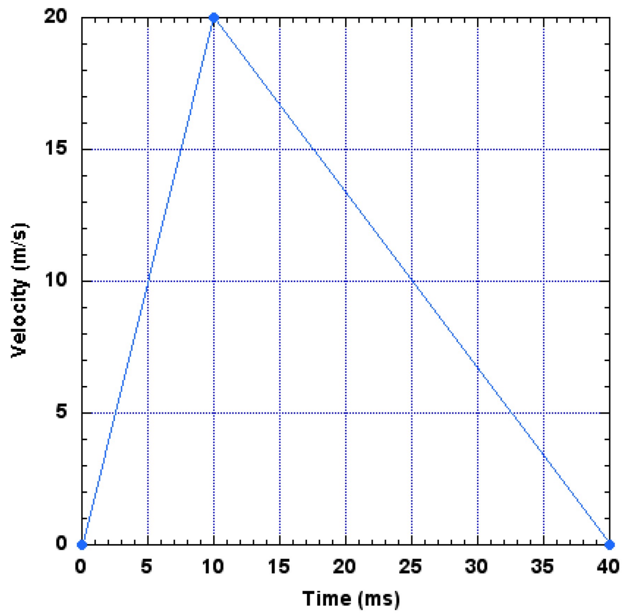
d) after the repeat loading; 40-cm displacement

Figure 14.

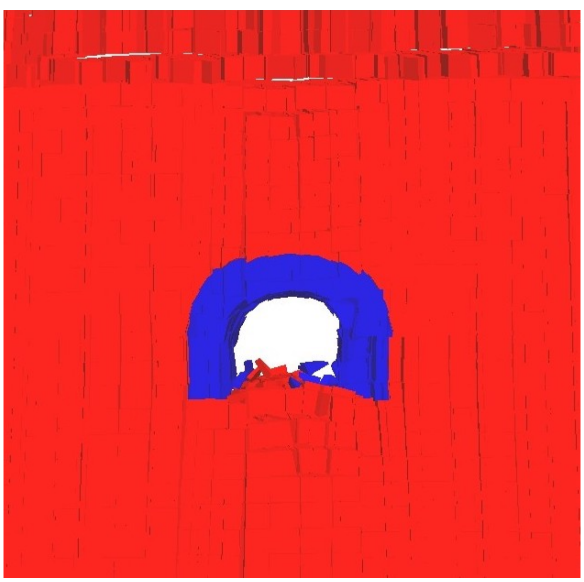
The last example of reloading uses the same rock island and rock mass as previously, but the tunnel now has a 1-m thick reinforced concrete liner (Figure 15a). The velocity pulse is stronger (Figure 15b). The results after the first and repeat loadings shown in Figures 15c and 15d indicate that there is no additional damage to the liner after the repeat pulse.



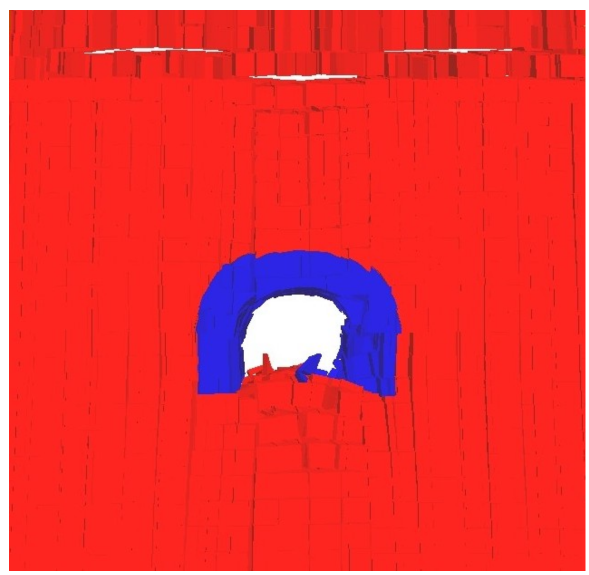
a) Initial condition



b) Applied velocity pulse



c) after the first loading; 20-cm displacement

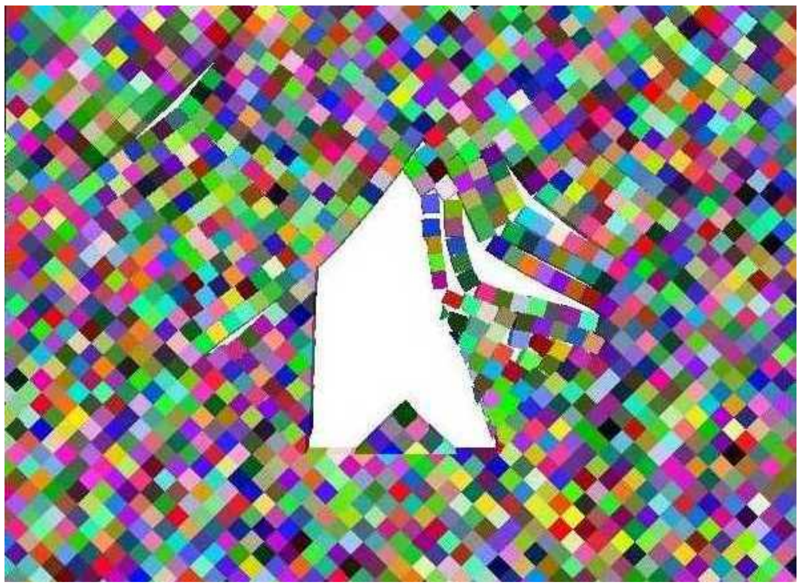


d) after the repeat loading; 40-cm displacement

Figure 15.

LDEC Simulations Compared to Actual Tunnel Failure Cases

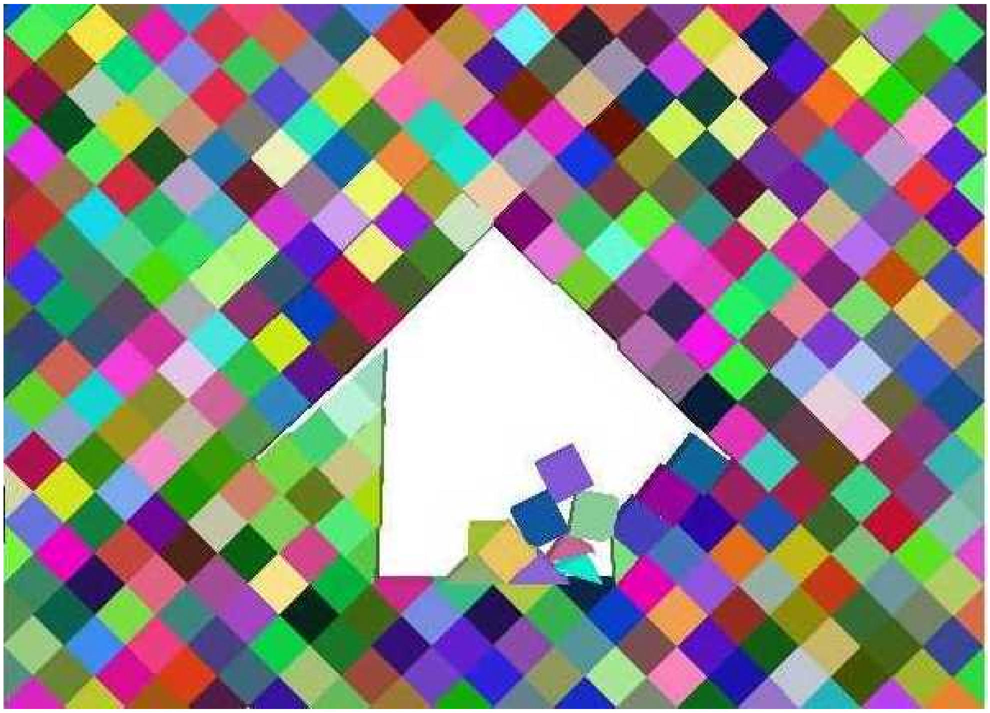
Clearly, it is essential to assess whether such simulations realistically relate to real-life tunnel behavior. To that effect, the authors selected from their files several examples of tunnel failures to be compared to the LDEC results. The comparisons, shown in Figures 10 through 12, indicate that these discrete element analyses capture very well the kinematics of tunnel failures under dynamic loading.



LDEC simulation showing buckling of thin rock layers

Ground failure in a Belgian coal mine, after a coal bump. The buckling of layers has been frozen in time and space by the steel support.

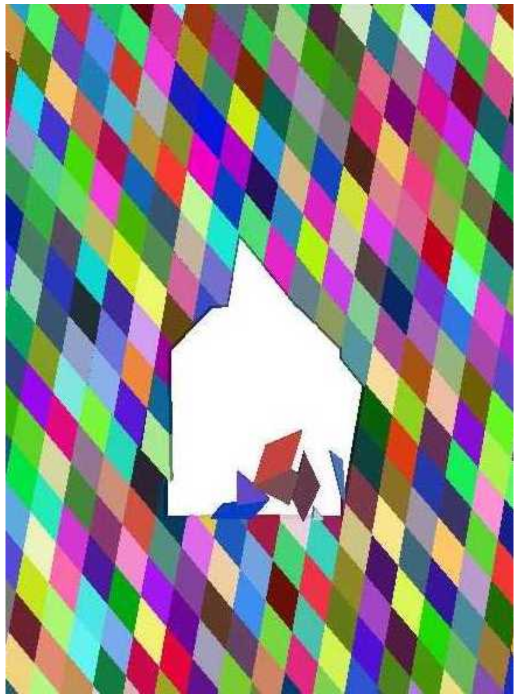
Figure 16



LDEC simulation showing a fairly symmetrical roof failure

Ground failure in a South African gold mine under a rock burst
(Courtesy of D. Ortlepp, 2003)

Figure 17



LDEC simulation showing a non-symmetrical roof failure controlled by jointing

Asymmetrical roof failure in a South African gold mine under a rock burst
(Courtesy of D. Ortlepp, 2003)

Figure 18

A Glimpse Into the Future

Recently the LDEC code was operated on "Thunder" a new supercomputer at the Lawrence Livermore National Laboratory (LLNL). This allowed the simulation of models of greater size and complexity than had previously been possible. The underground complex shown in Figure 19 spans 60m in each direction and includes several tunnel sections and a lift shaft. Figure 20 gives interior views of the facility.

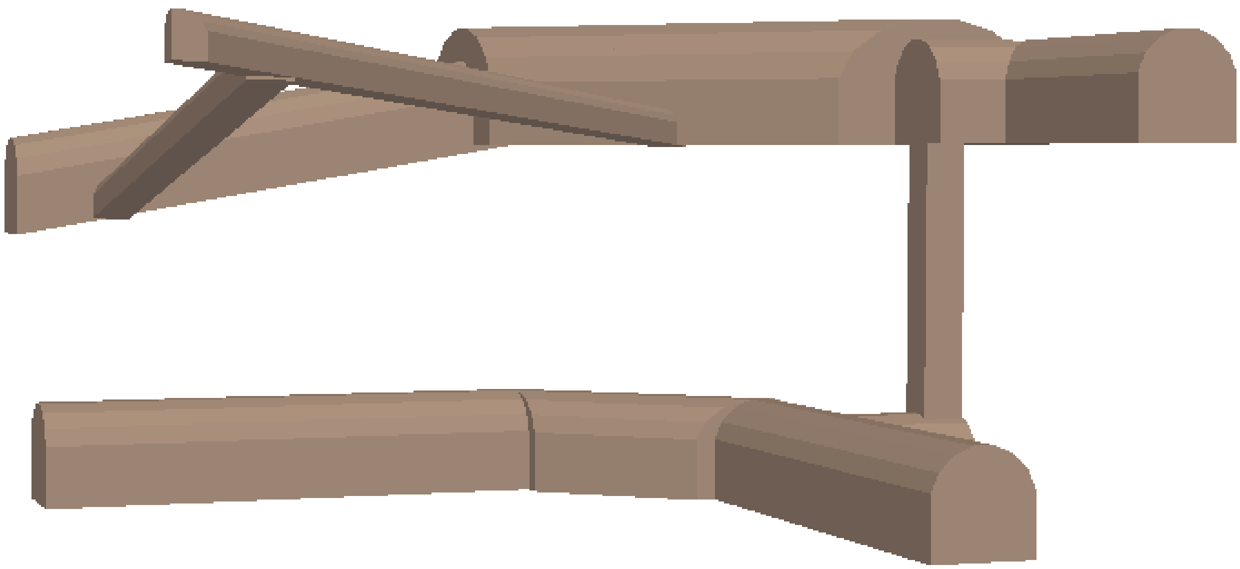


Figure 19. Underground complex simulated with the LDEC code. The typical block size is 30cm. The model has 8 million blocks and 100 million contact elements.

The top of the rock island containing the tunnel complex was subjected to a triangular velocity pulse. It resulted in a peak velocity of 4m/s at the roof of the upper chamber with a rise time of 1ms and a decay time of 19ms. So, the peak displacement was 4cm. Calculations performed on 3840 parallel processors ran to 300ms of real time in 4 days (42 years of CPU).

The effect of the loading pulse is illustrated in Figures 21 and 22. It is interesting to note that while the upper large chamber is completely destroyed, the small adjacent drift experiences a range of response going from full collapse close to the large opening, where the intersection degrades tunnel strength, to no damage at some distance.

The simulation of that complex was performed both with persistent joints and non-continuous joints. It showed that the continuous joints imparted a strong anisotropy to the rock mass and tended to channel the energy in preferred directions. That geologic structure also allowed more "chimneying" over the unstable openings. The non-continuous joints resulted in more diffraction of waves around the openings and less of a shadow effect on the lee side of the loading wave.

a) Inside view of the upper large chamber

b) View down the smaller tunnel on the left side of the above chamber

Figure 20. Inside views of the underground complex, before loading by the velocity pulse

a) The small tunnel seen from the upper chamber at 300ms appears to be completely destroyed

b) A view from inside the small tunnel shows that it is only partly collapsed

Figure 21. Impact of the velocity pulse on the small tunnel

Figure 22. Effect of the velocity pulse on the upper large chamber, at 300ms

Summary

A series of two-dimensional and three-dimensional simulations with the LDEC code has provided valuable insights into the response of tunnels in jointed rocks to dynamic loads. A summary of observations is as follows:

- 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 demonstrated quantitatively that joint spacing, or the ratio of spacing to tunnel mean dimension, is also a very influential parameter of tunnel strength.
- For dynamic loading, it was shown that both the pulse intensity and its duration intervene in the amount of damage created.
- 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 attain 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.
- It was also 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.

The paper concludes with a look into the future of discrete element simulations. The emerging ability to handle very large systems (many millions) of blocks bodes well for the rock mechanics and rock engineering community when it is faced with solving large-scale field problems.

References

1. Morris, J. P., Rubin, M. B., Blair, S. C., Glenn, L. A., and Heuze, F. E. "Simulations of Underground Structures Subjected to Dynamic Loading, Using the Distinct Element Method", Engineering Computations, v. 21, n. 2/3/4, pp. 384-408, 2004.

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