Simulations of explosion-induced damage to underground rock chambers

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Received in 19 January 2011; received in revised form 20 February 2011; accepted 25 February 2011

Abstract: A numerical approach is presented to study the explosion-induced pressure load on an underground rock chamber wall and its resultant damage to the rock chamber. Numerical simulations are carried out by using a modified version of the commercial software AUTODYN. Three different criteria, i.e. a peak particle velocity (PPV) criterion, an effective strain (ES) criterion, and a damage criterion, are employed to examine the explosion-induced damaged zones of the underground rock chamber. The results show that the charge chamber geometry, coupling condition and charge configuration affect significantly the dynamic pressure exerted on the rock chamber wall. Thus the chamber is damaged. An inaccurate approximation of pressure boundary ignoring the influences of these factors would result in an erroneous prediction of damaged area and damage intensity of the charge chamber. The PPV criterion yields the largest damaged zone while the ES criterion gives the smallest one. The presented numerical simulation method is superior in consideration of the chamber geometry, loading density, coupling condition and rock quality. The predicted damage intensity of rock mass can be categorized quantitatively by an isotropic damage scalar. Safe separation distance of adjacent chambers for a specific charge weight is also estimated.

Key words: underground explosion; rock damage; numerical simulation; safe separation distance

1 Introduction

The existing empirical methods for predicting the explosion-induced damaged zone around underground rock chambers [1–4] are mainly based on observations of different scaled field tests and some simplified analytical models. Basically, they give a rough estimation of the damaged zone in terms of (1) charge weight of an accidental or artificial explosion and (2) peak strain, peak stress or peak particle velocity (PPV) experienced in the surrounding rock mass of an underground chamber. However, since the influences of complicated rock sites, irregular chamber geometries, and nonuniform explosive configurations are ignored in the empirical predictions, it is questionable to use the empirical methods when these factors are involved. Moreover, these empirical methods cannot provide a reliable and quantitative estimation of rock mass damage under explosion-induced loads. On the other hand, numerical simulation using validated codes can consider various loading and coupling conditions, different material properties and rock chamber geometries very conveniently and thus can play a significant role in assessment of damaged zone and damage intensity of underground rock chambers subjected to explosion-induced load.

Numerous field tests have been conducted to characterize rock damage resulting from explosion-induced load [5, 6]. It is found that the rock mass damage decreases rapidly along the radial direction outwards from the charge chamber, tunnel or borehole for near surface detonation. For borehole blast, two major rock failure patterns may occur. One is the crushing zone that is mainly generated by very high pressure load around the charge borehole. The other is the extending individual radial cracks that is generated by circumferentially expanding deformation outwards from the crushing zone. The crack radius generated...
around a granite borehole by TNT explosion extends up to 4.9 times of the borehole radius, while the crushing zone covers only 1.9 times of the radius [5]. However, it should be addressed that the observations are based on some small-scale borehole blast tests. For a large-scale explosion test, the categorization of the rock mass damage will be much more complicated in an experimental manner. In a test reported by Olson et al. [4], crack in granite spread to a square-root distance of 0.8 m/kg$^{1/2}$. Hendron [3] summarized the observations of large explosion tests carried out by the U.S. Army Corps Engineers between 1948 and 1952 near unlined tunnels at sandstone and granite sites. He suggested that, on average, the rock in tunnels did not fail until the PPV exceeded 900 mm/s. When the PPV was 460 mm/s or larger, an intermittent failure would occur in the tunnels. Dowding [6] indicated that the cracking strains for granite and concrete were approximately the same as about 2 400 $\mu$e, while blowout occurred in granite when the cracking strain reached 3 800 $\mu$e. However, these empirical criteria of rock failure depend largely on rock quality and explosive configurations. Accurate estimation of the PPV and the effective strain (ES) is also an obstacle. So, the rock damage is categorized roughly. Esen et al. [7] reviewed the crushing zone prediction models used in mining engineering. They characterized the explosion-induced rock damaged area into a crushing zone, a fracture zone (with denser cracks) and a fragment formation zone (with fewer cracks) around the detonated borehole. The empirical estimations of the crushing zone size were given in terms of some factors including borehole radius, detonation pressure or energy, rock quality (modulus and strength). They showed that the crushing zone size depended highly upon the dynamic pressure exerted on the borehole wall. However, accurate estimation of the borehole pressure for a given explosive, especially in fully-coupled and slightly-decoupled detonation processes, is a very big challenge. If the borehole geometry is irregular and/or the explosive is arbitrarily distributed in the borehole, or an underground rock chamber or tunnel, analytical derivation of the dynamic pressure becomes impossible.

In a previous study [8], numerical simulations were carried out to investigate the influences of explosion conditions including loading density, explosive distribution pattern, chamber geometry, and chamber volume on explosion-induced stress wave propagation. A subsequent study [9] further investigated these explosion scenarios and estimated the damaged zones in a granite mass resulting from an accidental explosion in an underground ammunition storage chamber. On the basis of the numerical results, some empirical formulae were derived to predict peak particle acceleration (PPA), PPV and principal frequency of stress wave in the granite mass, the damaged zones around the explosion chamber, as well as the safe embedment depth of the storage chamber and safe separation distance between adjacent chambers. It was found that these explosion scenarios significantly affected the rock mass responses to explosion-induced loads. In the present study, numerical simulation of an underground rock chamber subjected to explosion-induced load is carried out again by employing the commercial software AUTODYN [10]. The effects of detonation process, air-pressure and chamber wall interaction, and rock mass responses to explosion-induced load are considered in the present simulation. Failure of the rock mass is modeled by a modified piecewise linear Drucker-Prager criterion, which is integrated into the software through user subroutines. Using this modified version of the software, the effects of charge geometry and explosive configuration are investigated. Rock damage is characterized by the maximum equivalent tensile strain experienced by the target. The simulation results are verified against those based on empirical criteria and test results [11, 12]. It is found that the proposed numerical method can be applied effectively to the evaluation of the explosion safety of underground rock chambers.

2 Damage model for rock mass

The commercial software AUTODYN has the feature of simulating detonation process directly, which saves the effort to derive the explosion-induced wall pressure. In the context, an Euler processor is used for the flowable TNT equivalent and the chamber void. Solid rock mass is modeled mathematically by a Lagrange processor. An Eulerian subgrid and a Lagrangian subgrid may interact through an Euler-Lagrange interface. In the Euler-Lagrange interface, the Lagrangian subgrid acts as a geometric constraint to the Eulerian subgrid, while the Eulerian subgrid provides a pressure boundary to the Lagrangian subgrid. As the Lagrangian subgrid moves and distorts,
it covers and uncovers the fixed Eulerian cells. The software utilizes a sophisticated logic to avoid overly small Eulerian cells that may arise during this process. Small Eulerian cells, which could severely limit the calculational timestep, are automatically blended with larger neighbors. The Euler-Lagrange interface allows complex fluid-structure interaction problems to be solved as well as the large deformation structural problems. Some details of the interaction algorithm of the Eulerian and Lagrangian cells can be found in Donea et al. [13, 14].

The partial differential equations to be solved represent the conservations of mass, momentum and energy in the Lagrangian coordinates. These, together with a material model and a set of initial and boundary conditions, define the complete equations governing the problem. Material associated with a Lagrangian zone stays with that zone at any deformation. Thus, a Lagrangian grid moves and distorts with the material it models, and conservation of mass is automatically satisfied. The density at any time can be determined from the current volume of the zone and its initial mass. In order to avoid hourglass to happen, a set of corrective forces are added to the solution [10].

In the study, the chamber wall is modeled as a separating boundary, which restricts the flow of Eulerian subgrid. The pressure due to the explosive energy release interacts with the chamber wall and thus produces stress wave in the surrounding rock mass. The simulation is initiated by the assignment of a detonation point on the meshed explosive. The high-energy TNT equivalent and the air filling chamber are modeled by the Jones-Wilkens-Lee (JWL) equation-of-state and the ideal gas equation-of-state, respectively, which are available in the material library of the software [10].

The calibration process of the numerical model has been done by simulating two small-scale field tests [11, 12]. One was conducted at a granite site [11] and the shock waves were generated by borehole blasting. The other was done at an abandoned limestone quarry site, where the rock chamber was 115 m beneath the ground surface. The calibration was mainly carried out for the grid size, the interaction between the Eulerian and the Lagrangian subgrids, and the proper implementation to the material model. Sensitivity of rock parameters to the numerical results was not included.

A piecewise linear Drucker-Prager failure criterion is used in the present study. It has the following form:

\[ \sqrt{J_2} + a_i I_i - b_i = 0 \quad (i = 1, 2, \cdots, N) \]  (1)

where \( I_i \) is the first stress invariant, \( J_2 \) is the second deviatoric stress invariant, \( a_i \) and \( b_i \) are parameters depending on the strength behavior of the rock material, and \( N \) is the number of the linear segments in the piecewise Drucker-Prager failure model. The parameters \( a_i \) and \( b_i \) (\( i = 1, 2, \cdots, N \)) for a given material can be determined by simple laboratory tests such as uniaxial tensile test, uniaxial compressive test and triaxial test. In the present study, four sets (\( N = 4 \)) of the experimental data are used to determine the following parameters:

1. Cutoff hydro-tensile strength \( f_{mt} \) (\( f_m = \sigma_1 = \sigma_2 = \sigma_3, \ f_m = f_i / 3 \));
2. Uniaxial tensile strength \( f_t \) (\( f_1 = \sigma_1, \ \sigma_2 = \sigma_3 = 0 \));
3. Uniaxial compressive strength \( f_c \) (\( \sigma_1 = \sigma_2 = 0, \ \sigma_3 = -f_c \));
4. Confined compressive strengths \( f_{cc} \) and \( f_{cc} \) (\( \sigma_1 = \sigma_2 = -f_{cc} < 0, \ \sigma_3 = -f_{cc} < 0 \)), where \( f_{cc} \) is the axial compressive stress, and \( f_{cc} \) is the confining stress.

The uniaxial compressive strength \( f_c \) and the uniaxial tensile strength \( f_t \) of the granite used in the present study are 148 and 19 MPa, respectively [15]. By curve-fitting to various existing experimental data [16], the confined compressive strengths for the proposed strength criterion have the following expression for intact rock:

\[ \frac{f_{cc}}{f_c} = \frac{f_{cc}}{f_c} + \sqrt{m f_{cc}^2 + 1} \]  (2)

where \( m = f_c / f_t \). Thus, for any confining stress \( f_{cc} \), the axial compressive stress \( f_{cc} \) is derived from Eq.(2). In the present numerical simulation, the confined compressive strength points of 2.7\( f_c \), 0.5\( f_c \) are used as the last set of the strength parameters.

Since damage and plastic flow may occur simultaneously, the yield strength decreases with the degradation of stiffness. Assuming that the post-failure of rock material satisfies isotropic softening rule, then, if \( a_i \) remains unchanged, \( b_i \) will degrade according to

\[ b_d = b_i (1 - D) \quad (i = 1, 2, \cdots, N) \]  (3)

where \( D \) is the rock damage to be defined later, and \( b_d \) is the material parameter for the damaged rock. Figure 1 illustrates graphically the modified Drucker-Prager failure model for intact and damaged rocks.

Damage of high quality granite [15] considered in the present study is modeled with an isotropic continuum damage criterion, providing that the rock mass is isotropic and homogeneous without significant
rock joint around the charge chamber. In the isotropic damage model, the cracked material is represented by damaged continuum material with equivalent overall degradation [17–19]. Damage growth is assumed to be governed by a loading surface in the strain space, which defines a unique relationship between the size of the damage surface and the accumulated damage [20].

The damage scalar is determined by a crack density function, which is again determined by an equivalent tensile strain. The crack density function used is similar to that defined by Liu and Katsabanis [17]. It has the forms as follows:

$$C_d = \alpha \langle \varepsilon - \varepsilon_{cr} \rangle^\beta \tau$$

$$E = \sqrt{\sum_{i=1}^{3} (\varepsilon_i)}^2$$

where $E$ is the equivalent tensile strain; $\varepsilon_i$ ($i = 1, 2, 3$) is the principal strain; the angular bracket $\langle \cdot \rangle$ denotes that the function is valid only when the value inside the bracket is larger than zero; $C_d$ is the total number of cracks per unit volume; $\alpha$ and $\beta$ are material constants; $\varepsilon_{cr}$ is the critical tensile strain, at which damage initiates; and $\tau$ is the accumulated time of damage.

The damage scalar is then directly defined as

$$D = 1 - e^{-C_d^2}$$

where $V$ is the unit volume.

Thus, if the equivalent tensile strain exceeds the critical value $\varepsilon_{cr}$, the material stiffness and strength would degrade. The damage scalar $D$ ranges from 0 to 1 according to Eq.(6). The parameters used in the study are listed in Table 1. The present material model was implemented in AUTODYN and validated by two field explosion tests [11, 12].

### Table 1 Properties of rock mass (granite).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference density (kg/m$^3$)</td>
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</tr>
<tr>
<td>Bulk modulus (GPa)</td>
<td>41</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>27</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>67</td>
</tr>
<tr>
<td>Uniaxial compressive strength (MPa)</td>
<td>148</td>
</tr>
<tr>
<td>Uniaxial tensile strength (MPa)</td>
<td>19</td>
</tr>
<tr>
<td>Yield stress $\sqrt{\sigma_2}$ (MPa)</td>
<td>$6.9 \times 10^3$</td>
</tr>
<tr>
<td>Damage parameters $\alpha$, $\beta$</td>
<td>2, 0.287 × 10$^{-5}$</td>
</tr>
<tr>
<td>Critical tensile strain, $\varepsilon_{cr}$</td>
<td>0.287 × 10$^{-5}$</td>
</tr>
</tbody>
</table>

3 Explosion-induced chamber wall pressure

The configuration of underground explosion simulated in the context is schematically shown in Fig.2. The cover thickness of the underground chamber is defined as the vertical distance from the ground level to the chamber ceiling. A cover thickness of $1.0Q^{1/3}$ in meter, where $Q$ is the explosive weight in kilogram, is used in the numerical model. The cover thickness of $1.0Q^{1/3}$ is specified by the DoD standard [2] to prevent rock cover from breakage during an underground explosion event. It is a pure empirical value, thus has an unusual unit. The pressure on the rock chamber wall is calculated automatically by the software, which is an obvious advantage over analytical or empirical methods that are unable to solve the interaction between the shock pressure and the chamber wall, especially when the geometry of the rock chamber is irregular or the explosive is contained arbitrarily.

However, it is worth noting that the present numerical model does not consider the effects of the protective constructions and the roughness of the rock chamber is not taken into account either.

Interaction between the explosion-induced pressure wave and the solid rock chamber wall is very complicated. Different waveforms, i.e. overpressure, reflected pressure and transmitted pressure, may be used to characterize the effect of the shock wave on the chamber wall. The overpressure propagating in free-air attenuates following a cubic root rule of the direct distance for a given charge weight. Away from the charge center, the time-history overpressure has the shape shown in Fig.3. However, in a contained explosion, interaction between the explosion wave and the rock chamber wall produces various reflected pressures in the chamber and transmitted pressures into.
the rock mass. The reflected pressures and the transmitted pressures are more important in identifying the rock chamber damage and the stress wave propagation in the rock mass. Their magnitudes and waveforms depend on the factors including chamber geometry, coupling condition, and explosive configurations. A traditional way in simulating the explosion-induced load is to apply uniformly distributed time-history pressure or time-history velocity to the rock chamber wall, while the pressure or velocity time-histories are estimated by the charge weight and energy, loading density (charge weight per chamber volume), etc.. It should be mentioned that, the empirically-estimated pressure (or sometimes velocity) boundary condition usually ignores the interaction between the air-pressure and the chamber wall. If it is directly applied, the simulated chamber wall damage and the subsequent stress wave transferred into the rock mass would be very different. Furthermore, although, for some simple chamber geometries and symmetrical explosive setups, prediction of the overpressure and the reflected time-history pressure based on simplified analytical solutions may be possible, the evaluation of the transmitted pressure will be difficult if the material properties of the rock mass are nonlinear. For complicated charge conditions and chamber geometries, accurate prediction of the pressure boundary condition by using the simplified analytical solutions is almost impossible.

Traditional simulations of underground explosion generally use a simplified configuration of the charge chamber such as the one shown in Fig.4(a). In the spherical charge condition, the reflected pressure and the transmitted pressure depend only on the charge weight and the loading density. However, in more complicated cases, as shown in Figs.4(b)–(d), the transmitted pressure and the damaged zone around the chamber are affected by the charge chamber geometry and the coupling condition besides the loading density and the charge weight. The difference among these models can be demonstrated by comparing the transmitted pressures of different explosive configurations, as shown in Figs.4(a)–(d).

In the spherical charge condition, the present numerically simulated reflected pressure and transmitted pressure generated by a 250-t TNT explosive with a loading density of 10 kg/m³ are illustrated in Figs.5(a) and (b), respectively. In the simulations, the rock material is assumed to be elastic and an axisymmetrical model is used. When the total charge weight and the loading...
density are fixed, the chamber volume can be determined accordingly in spite of the chamber geometry. The reflected time-history pressure is measured at a point in the air media near the chamber wall, while the transmitted time-history pressure is recorded on the rock chamber wall. It is shown that the waveforms of the reflected pressure and the transmitted pressure are very different even in the perfectly symmetrical case. The peak reflected pressure is around 76 MPa followed by a series of periodical second-order peak pressures. The subsequent peak pressure is produced by the chamber wall re-reflection. However, almost all the shock energy transmitted into the rock media is concentrated in the first period of time of the reflected pressure. The peak transmitted pressure is about 30 MPa, which is much lower than that of the reflected pressure. Negative phase of the dynamic pressure is observed simply because the rock material is assumed elastic, i.e. no material failure is involved.

However, when the charge chamber section is rectangular (Fig.4(b)) and the explosive is placed on the chamber floor, as shown in Fig.4(c), the dynamic pressures at different locations on the chamber wall vary. Figure 6 illustrates the simulated pressure time-histories at four different locations on the chamber wall with an explosive of 250-t TNT placed on the floor center (Fig.4(c)). The loading density is 10 kg/m³ and the chamber height is 10 m. At target #1, which is at the center of the chamber ceiling, the peak transmitted pressure is about 510 MPa. At target #2 at the floor center, however, the peak transmitted pressure is over 3 363 MPa. It is much higher than that in the spherical charge case shown in Fig.5(b), whose charge weight and loading density are the same as those in Fig.6. At targets #3 and #4 on the chamber ceiling and floor, the peak values reduce drastically to about 62 and 31 MPa, respectively. The duration of pressure histories and the arriving times at targets #3 and #4 are also very different from those at targets #1 and #2. Because the piecewise linear Drucker-Prager failure model has been applied to the rock mass in this case, the negative parts of the transmitted pressure that

![Fig.5 Waveforms of reflected pressure and transmitted pressure.](image1)

![Fig.6 Transmitted pressures at different locations on rock chamber wall.](image2)
produces rock spalling are filtered to a very low level. The results indicate that the charge chamber geometry and the explosive configuration affect significantly the transmitted pressure in the rock mass. Ignoring these effects may lead to erroneous estimations of the transmitted pressure, the rock mass damage in the surrounding rock and the subsequently propagating stress wave. Accurate damaged zone prediction, thus, is almost impossible no matter what advanced material model is adopted for the rock mass.

4 Simulations of explosion-induced underground chamber damage

The present numerical method using the modified version of AUTODYN is then applied to an underground rock chamber detonated by a 250-t TNT explosive. The cover thickness is again expressed as $1.0 Q^{1/3}$, i.e. 63 m from the chamber ceiling. Three different rock damage criteria, i.e. the PPV criterion [3], the ES criterion [6], and the above proposed damage criterion (see Section 2), are adopted to estimate the damaged zone around the charge chamber. The PPV is defined as the maximum value of the resultant response velocity. The effective strain is calculated by

$$\varepsilon_{EP} = \frac{1}{\sqrt{2}} \sqrt{(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2}$$  \hspace{1cm} (7)

For a plane wave, the particle velocity ($v$) and the effective strain has the following relation:

$$\dot{\varepsilon}_{EP} = \frac{dv}{dx}$$  \hspace{1cm} (8)

where $\dot{\varepsilon}_{EP}$ is the rate of change in the effective strain, and $x$ is the plane wave direction.

Figure 7(a) shows a typical mesh for the underground explosion simulation. Figure 7(b) is the simulated pressure distribution at a certain instant. The PPV of 0.9 m/s and the $\varepsilon_{EP}$ of 3 800 $\mu$e are adopted as the thresholds of crushing failure of hard rock to give the major damaged zone around the rock chamber. Results based on these two empirical criteria serve as the calibration samples for those based on the proposed rock damage criterion. Figure 8 shows the damaged zones of the rock chamber based on the PPV criterion ($PPV > 0.9$ m/s) and the ES criterion ($\varepsilon_{EP} > 3 800$ $\mu$e), respectively, with a loading density of 10 kg/m$^3$ and a chamber height of 10 m. The explosive (250-t TNT) is placed at the center of the chamber floor. The damaged zone based on the PPV criterion is larger than that based on the ES criterion. Minor damage occurs on the ground level because of the stress wave reflection from the free surface.

When the chamber height changes to 20 m while the charge weight and the loading density remain 250 t and 10 kg/m$^3$, respectively, the simulated damaged zones are significantly reduced, as shown in Fig.9. It is observed from Fig.9 that the rock damage near the floor center is much larger than that on the chamber ceiling. It also indicates that the coupling condition has a significant effect on the damaged zone for a given
loading density, and uniform pressure boundary derived based on the charge weight and the explosive energy will result in completely a different damage profile of the rock chamber. It may be said that the damage of rock chamber depends on not only the loading density but also the chamber geometry. Again, larger damaged area is observed when the PPV criterion is employed.

Figure 9 gives the damaged zones for the two chambers based on the proposed damage criterion when the explosive is hung on the chamber center. As expected, damage to the chamber floor is reduced, while the damage to the chamber ceiling is increased. The 20 m-high chamber produces a smaller damaged area around the chamber. The results indicate that the coupling condition has a significant effect.

To consider the influence of explosive distribution, two chambers with different charge distributions are investigated. In the first chamber, a 100-t TNT is placed at the center of the floor and another 150-t TNT is placed in a ring with a radius of 10 m on the floor. In the second chamber, all the 250-t charge is distributed in a ring with a radius of 10 m on the floor. The derived damaged zones for the 10 m-high chamber are shown in Fig.11. It is observed that the second chamber produces a relatively larger surrounding damaged zone. However, the first chamber causes a more concentrated damage to the rock mass around the center of the chamber. Both chambers result in smaller failure areas at the ground level compared to the case of a concentrated charge on the chamber floor shown in Fig.11(a). It indicates that different explosive distributions will induce different damaged areas and damage levels around the chamber.

The major damaged zones based on the proposed criterion ($D > 0.22$) in the study for the two cases are shown in Fig.10. It can be observed that the damage intensity above the chamber is much lower than that on the chamber floor. However, the damaged zone size is about the same on the top and bottom sides, while singular damage is produced near the sidewall. The predicted damaged area is between the results based on the PPV criterion and the ES criterion. This indicates that the proposed damage model is effective. It is seen again that minor rock spalling occurs on the ground level due to the stress wave reflection from the free boundary. The chamber with a height of 20 m experiences a smaller damaged zone, which implies again that the chamber geometry has a significant effect on the damage profile.
The results demonstrate that numerical prediction of rock mass damaged areas based on the proposed damage model is comparable with the results based on the empirical criteria (PPV and ES criteria). The two empirical criteria are based on different underground explosion tests [6]. Because quantitative identifications of rock damage are very difficult in a large-scale explosion test, the two threshold values of \( PPV \) and \( ES \) may be very subjective. Numerical prediction of rock damage is more versatile than field tests for it can easily take into account different materials and geometrical properties of a site. It also gives quantitative descriptions of damage levels at various locations from the charge center. The results also show that the dynamic pressure applied on the chamber, the damaged area as well as the damage level around the chamber all depend on not only the loading density but also the chamber geometry, and the charge location and distribution. These observations are consistent with those made by Wu and Hao [9].

5 Separation distance between adjacent chambers

Odello and Price [1] reviewed data from a few field tests and recommended that a separation distance of \( 0.6Q^{1/3} \) (in meter) between chambers was required to prevent the propagation of explosion resulting from high-speed rock spalling, and \( 2.5Q^{1/3} \) (in meter) to prevent damage in adjacent chambers. It was assumed that the chambers were unlined and the rock was granite. Safe separation distance between two chambers regulated by the DoD standard [2] requires a minimum distance of \( 1.0Q^{1/3} \) to prevent hazardous spalling; and \( 0.6Q^{1/3} \) to prevent explosion communication by spalled rock when there is no special protective construction in the acceptor chamber, and the separation should be \( 0.3Q^{1/3} \) when the acceptor chamber has protective constructions. The rock type corresponding to these specifications is either moderately strong or strong, and the loading density must be less than 50 kg/m\(^3\).

Numerical simulation using the proposed method is then implemented to evaluate the safe separation distance for the underground chambers. The charge chamber is 10 m in height and 12.6 m in radius. The charge weight is equivalent to 100-t TNT, which gives a loading density of 20 kg/m\(^3\). The adjacent chamber, which has the same height and 12.6 m in width, surrounds the charge chamber since an axisymmetrical model is used in the simulation. The separation distance between the two chambers is 46 m (\( 1.0Q^{1/3} \)), which is the minimum separation distance required by the DoD code [2] to prevent hazardous spalling in the acceptor chamber. Figure 13 gives the numerical results of crushing zones in the rock mass based on the PPV criterion (\( PPV > 0.9 \) m/s), the ES criterion (\( ES > 3800 \mu \varepsilon \)) and the proposed damage criterion (\( D > 0.22 \)), respectively. As seen from Fig.13, the damage to the charge chamber is severe. However, based on all the three criteria, there is no rock spalling in the adjacent chamber with the separation distance of \( 1.0Q^{1/3} \). The PPV criterion again gives the largest estimation of damaged zone, while the ES criterion results in the smallest one.

Figure 14 shows the calculated damaged zones based on the three criteria when the separation distance is 14 m (\( 0.3Q^{1/3} \)). It should be mentioned that \( 0.3Q^{1/3} \) is the minimum separation distance specified by the DoD standard [2] when the acceptor chamber has protective constructions. As it can be seen, the acceptor chamber
Based on the PPV criterion.

Based on the ES criterion.

Based on the proposed damage model.

**Fig.14** Damaged zones based on various criteria when the separation distance is 14 m.

and rock mass between the two chambers are damaged severely, indicating that the protective constructions such as special linings are necessary if the separation distance is designed as $0.3Q^{1/3}$.

The damaged zones estimated based on the ES criterion and the proposed damage criterion are about 3 times of the charge chamber height in depth, while the damage in the radial direction is much smaller (less than 2 times of the chamber height). Based on the PPV criterion, the damaged zone is about 5 times of the chamber height in depth. These results are comparable with the experimental observations that the cracking zone extends to 4.9 times of the charge radius and the crushing zone extends to 1.9 times of the radius [5]. However, the accurate justifications for the damage criteria are not possible because large-scale test results regarding rock chamber damage are very rare. The present study provides a numerical approach, which intends to characterize the effect of different configurations of underground explosion. However,

the accuracy of the estimations requires systematically theoretical and experimental validations, especially for the highly decoupled large-scale underground explosions.

Using the numerical results, attenuation of the $PPV$ along the radial direction can be deduced. The $PPV$ attenuation variation is derived by curve-fitting with the scaled distance $(R/Q^{1/3})$ for the given charge weight (100-t TNT herein) and the charge setup (see Fig.13), which can be written as follows:

$$PPV = 0.56 \left( \frac{R}{Q^{1/3}} \right)^{-0.728}$$

The distance is thus derived in terms of $PPV$ and the charge weight as

$$R = 0.45(PPV)^{1.37}Q^{1/3}$$

Based on the PPV criterion ($PPV > 0.9$ m/s), the safe separation distance $R$ is calculated to be $0.52Q^{1/3}$, or 24 m based on Eq.(10). Figure 15 shows the damage scalar and $PPV$ values at different distances from the charge chamber wall. It can be seen that the safe separation distance is about 22 m when the damage scalar equals 0.22. Thus the safe separation distance estimated by the proposed damage criterion is a little bit smaller than that based on the PPV criterion, which is 24 m in the present case. From Fig.15, the damage intensity along the radial direction of the charge chamber is clearly identified by using the damage criterion. The rock damage has reached 1.0 in the area of $R \leq 16$ m, the damage scalar decays from 1.0 to 0.22 when the distance varies from 16 to 22 m, while the damage scalar reduces to zero when the distance is larger than 32 m.

**Fig.15** Safe separation distances based on different criteria.

### 6 Conclusions

Through the above discussions on the numerical results, it is demonstrated that the numerical method proposed in the context predicts effectively the
explosion-induced damage of underground rock chamber. Compared with the numerical results, the empirical methods, which usually ignore the influences of chamber geometry, coupling condition and charge configuration, can result in a very different damage pattern of the charge chamber. The PPV criterion always predicts the largest damaged zone of the chamber while the ES criterion gives the smallest one. The damage criterion proposed in the study is able to categorize the damage intensity quantitatively. The rock damaged areas based on the proposed damage criterion go between those based on the PPV and the ES criteria. Safe separation distance for a certain configuration of underground explosion predicted based on the proposed damage criterion is consistent with the design specification. However, the damage distribution is more clearly identified by the present numerical simulation method. Furthermore, the proposed numerical method is versatile in simulation of more complicated underground explosion configurations.

It is worth noting that the present study is based on continuum damage mechanics. The effects of the existing rock faults, joints and fractures are not taken into account in the numerical simulations. The present model employs an axisymmetrical model, which may be extended to three-dimensional cases within the computer capacities. Besides, large-scale explosion test results regarding the rock chamber damage are very rare. To validate the numerical simulations results, a lot of theoretical and experimental efforts of large-scale field tests are needed.

A validated numerical model for simulating the rock damage due to underground explosion will be very useful for underground ammunition storage design and protection of underground facilities in the near field. However, for practical application, the rock mass quality and morphology, fault and joint information, etc., may also affect significantly the numerical results. A three-dimensional analysis of the underground chambers, including the protection constructions, is also necessary for engineering problems.

References


