International Journal of Rock Mechanics & Mining Sciences 67 (2014) 88–95

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Study on the mechanism of zonal disintegration around an excavation

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ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form
16 June 2013
Accepted 29 December 2013

Keywords:
Zonal disintegration
Defects
P-wave
Cracked zone

ABSTRACT

Zonal disintegration is a curious phenomenon and has received considerable attention recently. Using traditional static mechanics cannot well explain the phenomenon of the alternately distributed cracked zones. In this paper, the process of a slowly unloading P-wave reflecting from a free surface has been investigated and the result shows that as a slowly unloading P-wave encounters a free surface, it could cause the phenomenon of zonal disintegration. In order to confirm this result, two numerical models of defected rock around an excavation under the action of a slowly unloading P-wave are established. The slowly unloading P-wave is induced by a steel plate impacting the target rock with a proper speed, and their interaction lasts for a long time. The simulation results show that if the strength of slowly unloading P-waves is in a certain range, the phenomenon of zonal disintegration could be observed, and if the incident wave is not a slowly unloading P-wave, such as a rectangle wave, the phenomenon of zonal disintegration will not occur.

1. Introduction

It is well known that in underground rock engineering, excavations will induce damages around an excavation, and this damaged zone can be divided into several sub-zones, such as plastic zones and loose zones. However, many in-situ results from South Africa, Russia and China showed a curious phenomenon of zonal disintegration existing around excavations in deep mines, and this has received considerable attention recently in the field of rock mechanics and rock engineering. The zonal disintegration refers to that the distribution of cracked zones is not integrated, but layered, and the cracked layers distribute alternately with the intact layers as shown in Fig. 1.

The phenomenon of zonal disintegration was first observed in Talnakh–Oktyarb mine at the depth up to 1050 m. The test results by Adams and Jager [1] from Witwatersand gold mine in South Africa showed that generally the thickness of intact zone was about 1.0 m, and the alternately distributed zones could extend to 12 m from the working face.

In-situ experiments in Taimyrskii mine of Russia by Shemyakin et al. [2–5] showed that 'around a tunnel, there are zones of fissured and non-fissured, propagating discretely into the depth of surrounding rock mass'. They pointed out that the thickness of the cracked layers was about 1.0–1.5 m, and the thickness of the intact layers was also about 1.0–1.5 m, and the number of cracked layers usually was more than 3 around a tunnel.

Using detector through boreholes in Huainan mine of China, Li et al. [6] observed that zonal disintegrations did exist, and they presented their measurement result of the alternately cracked layers as shown in Fig. 2. Similar results have been obtained by the in-situ velocity tests by using ultrasonic waves in Jinchuan mine of China [7] and by measuring the multipoint displacements in a Ni mine in China [8].

It is very imperative for us to clearly understand the mechanism of zonal disintegration due to its significant effect on the stability of underground engineering structures. It could be related to many underground engineering disasters, such as rockbursts and coal-gas outbursts. Unfortunately, until now, zonal disintegration is still complex for us, and the mechanism of zonal disintegration is still not clear. The traditional static mechanics theory cannot well explain the phenomenon of the alternately distributed cracked zones around excavations. Under this scenario, the best approach to the study is first to generate an extensive experimental database, and based on this database to perform a theoretical study. At the same time, it is essential to investigate the mechanism through numerical models so as to obtain a better understanding of the dominant parameters that control zonal disintegration.

Recently, many methods, such as in-situ observations, theoretical analyses, numerical simulations, and model tests, are implemented to investigate the curious phenomenon of zonal disintegration. Some researchers [9,10] investigated the mechanism of zonal disintegration through theoretical study, and tried to determine the range of zonal disintegrations. Some researchers [11,12] studied the special

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http://dx.doi.org/10.1016/j.ijrmms.2013.12.017
1365-1609

phenomenon of zonal disintegration by the numerical method. Through model tests, Gu et al. [13] studied the mechanism of layered fracture within the surrounding rock of a tunnel in a deep stratum. Pan et al. [14] employed gesso material to model a tunnel, but they failed to find zonal disintegration phenomenon. Shemyakin et al. [2–5] also conducted model tests in a laboratory to investigate the zonal disintegration phenomenon they observed in Taimyrskii mine. Sellers and Klerck [15] investigated the discontinuity effect on zonal disintegration. Zhang et al. [16] used a 3D geomechanical model to investigate zonal disintegration inside surrounding rock mass of a deep tunnel. Tan et al. [17] have explored a zonal disintegration

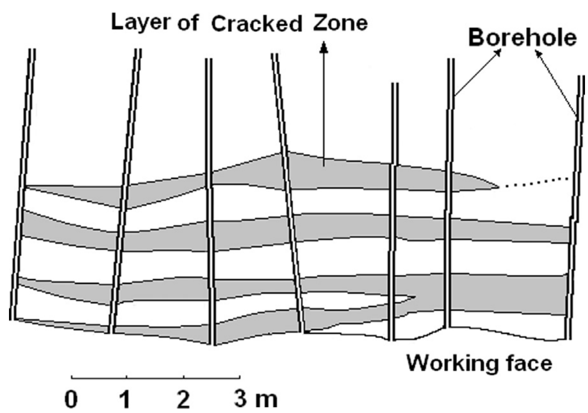

Fig. 1. In-situ testing results of the distribution of the cracked layers from Witwatersand gold mine of South Africa (according to [1]).

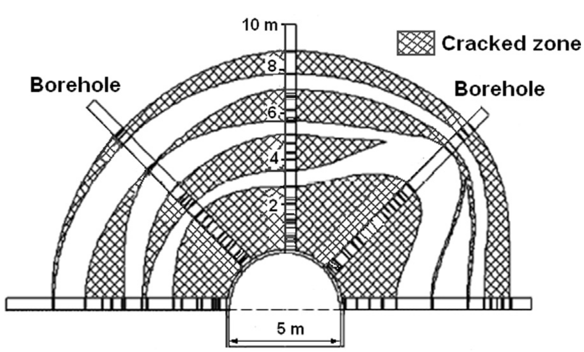

Fig. 2. Distribution of cracked zones in Huainan mine of China (according to [6]).

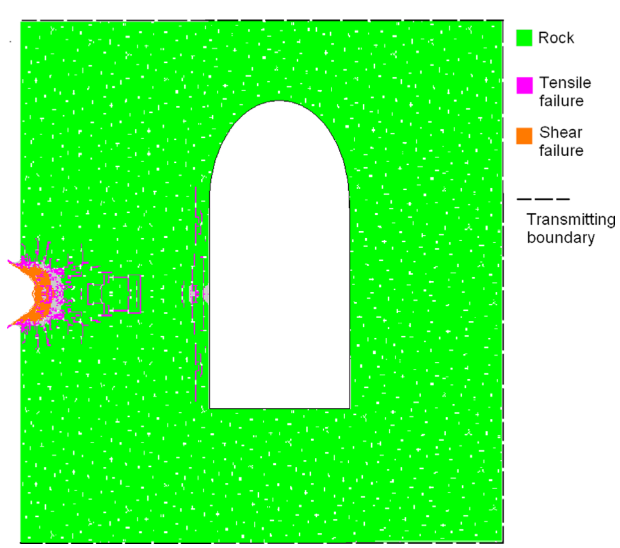

Fig. 3. Blasting induced spalling cracks near a tunnel surface.

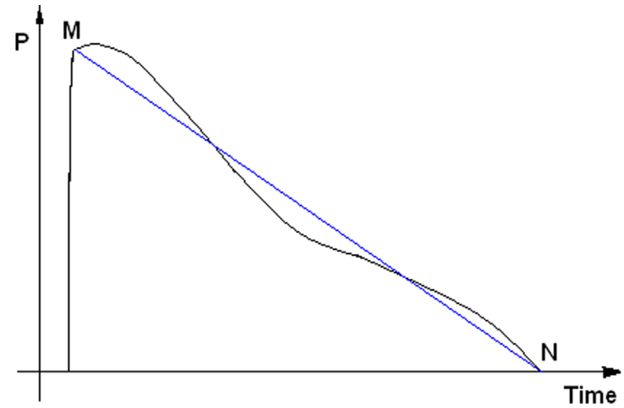

Fig. 4. A slowly unloading P-wave.

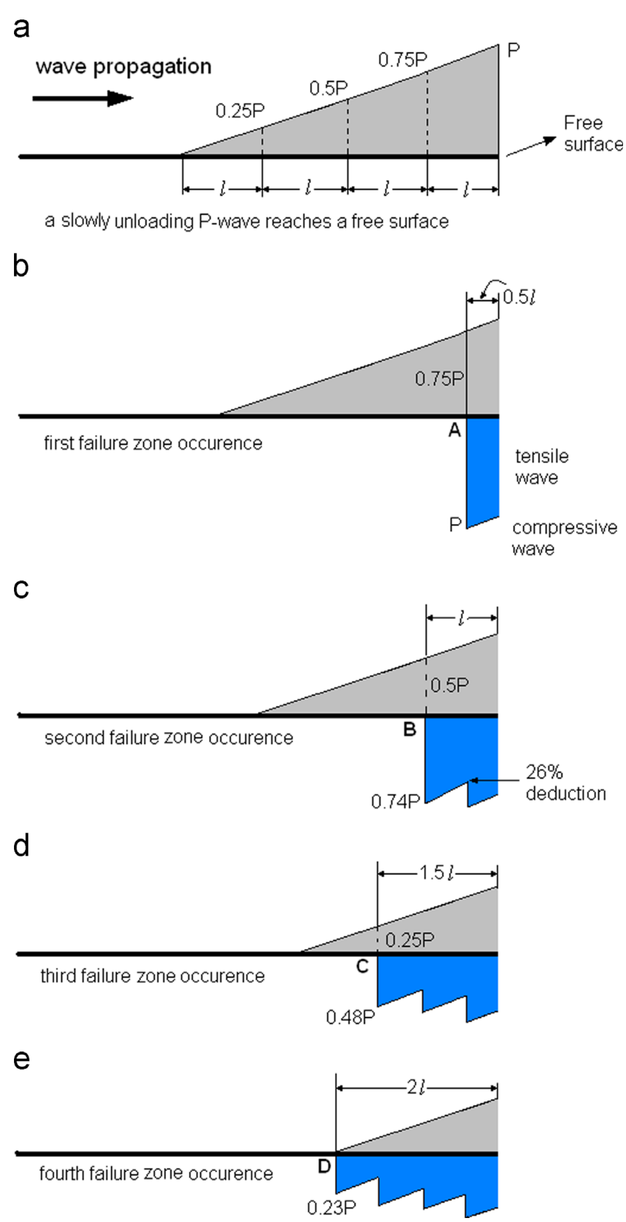

Fig. 5. Sketch illustrating the mechanism of zonal disintegration under a slowly unloading P-wave around a free surface; after a failure zone, the amplitude of the wave will reduce, and suppose the deduction is 26%.

developing process by in-situ observation through borehole cameras, and they pointed out that the mechanism of zonal disintegration in deep coal mines has a little difference from other deep rock engineering. Besides high stress, unloading by excavation and strong dynamic load like seismic, weak structure and longwall mining actions are key consideration influences on deep coal mines. Although many significant results have been published, we are still not very clear about the mechanism of zonal disintegration, and it has become a big curious phenomenon in rock mechanics.

The objective of this paper is to find the mechanism of zonal disintegration. Apparently, static mechanics cannot well explain the phenomenon of zonal disintegration around an excavation, and therefore, we have to consider the dynamics method. There are usually two kinds of dynamic loads: blasting and seismic wave. According to the author's previous work [27], blasting can induce spalling cracks near a tunnel surface as shown in Fig. 3, but blasting cannot induce zonal disintegration around an excavation, and therefore, seismic waves, specifically slowly unloading P-waves, are considered. In this paper, the process of a slowly unloading P-wave reflecting from a working face (free surface) will be investigated, and the corresponding numerical study will be implemented. Rocks usually contain defects, such as voids, pores, cracks and joints, and only the defects of voids and pores are considered. For brittle materials without defects, numerical studies have been implemented by a number of researchers using various numerical codes and models to simulate the processes of rock fracturing and fragmentation under dynamic loads [18–26]; however, for brittle materials with pre-existing defects (voids and pores), the achievements are limited. Defects consist of small free surfaces, and as stress waves cross defects, they will suffer both partial reflection and transmission. Therefore the borders of defects are treated as free boundary, which means that as stress waves encounter defects, they will suffer reflection. The study results show that around an excavation, a slowly unloading P-wave could induce the phenomenon of zonal disintegration.

2. Slowly unloading P-wave and the mechanism of zonal disintegration

P-waves are a major widely existing stress wave and they could be induced by an impact, a mining activity, a blast or an earthquake.

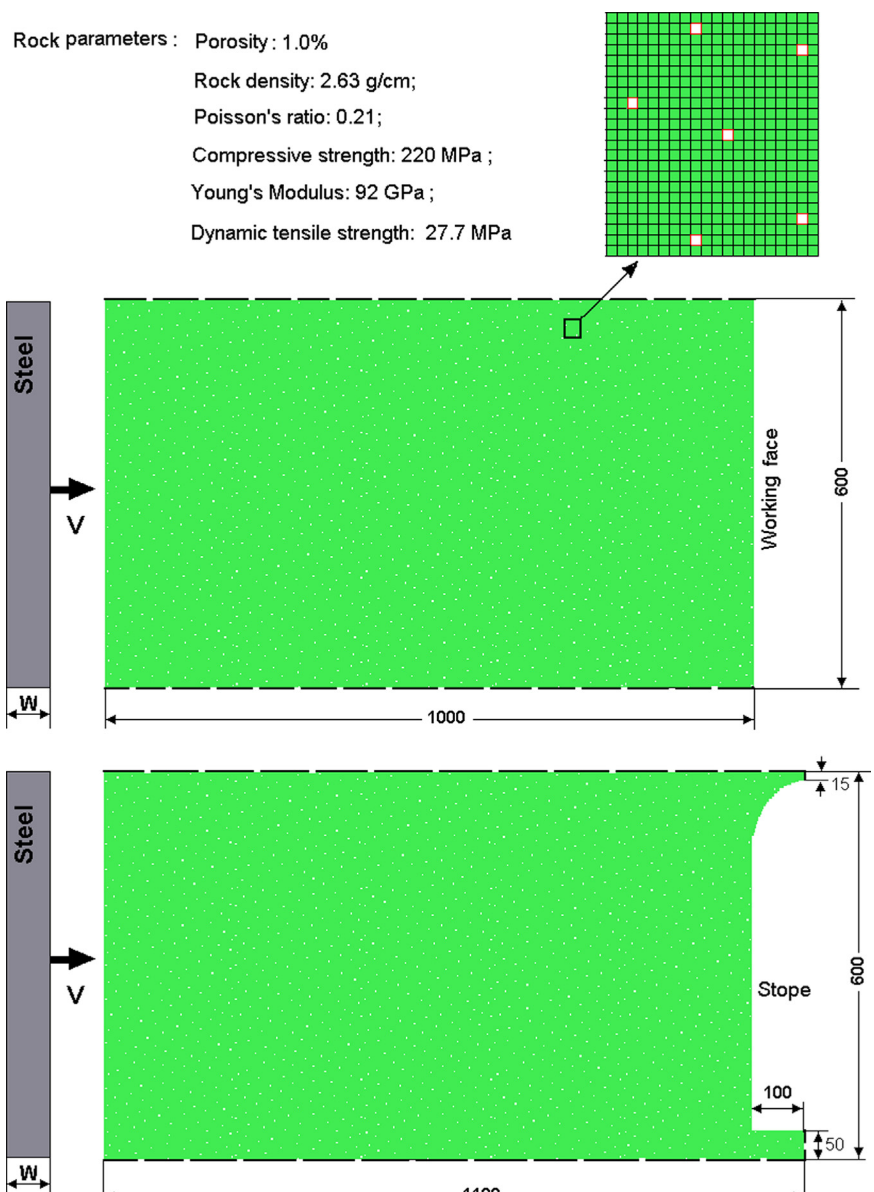

Fig. 6. Two numerical models for defected rock around an excavation under the impact of a steel plate with a proper speed; the dashed lines represent transmitting boundary.

As the unloading process takes a long time, the P-wave is called a slowly unloading P-wave. Suppose there are two plates A and B, and the relation between their material impedances is $\rho_A C_A > \rho_B C_B$. If plate A impacts plate B with a proper speed, then after impacting they may still interact together for a long time, and accordingly the P-wave induced by this impact will unload for a long time. An earthquake also could cause such slowly unloading P-waves because underground rock mass generally interacts together. Fig. 4 shows a slowly unloading P-wave, and in order to simplify the unloading path, the curve part will be replaced by a straight line MN.

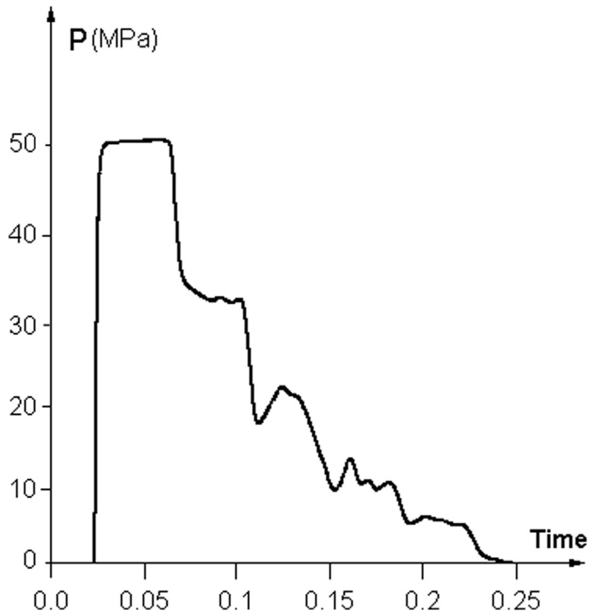

Fig. 7. A slowly unloading P-wave produced by a steel plate impact with a pressure of 51.5 MPa recorded from a point near the touching edge of the target rock.

When a slowly unloading P-wave encounters a free surface, it will reflect back and change from compressive to tensile. In order to illustrate the mechanism of zonal disintegration, suppose the maximum amplitude of the stress wave is P, and the whole P-wave unloading path is equally divided into 4 parts in x-axis, as shown in Fig. 5(a), and the rock material tensile strength is $0.2P$. From Fig. 5(b), one can find that around point A which is just $l/2$ to the free surface, the reflected tensile stress is $0.25P$ $(P-0.75P)$ which is larger than the material tensile strength $0.2P$. Therefore, a first group of tensile failure zone occurs.

After a group of cracks occurs, since the cracks will open, the amplitude of the reflecting tensile wave will be reduced due to the energy spent in the cracking process. Suppose there is 26% deduction after cracking. As the reflected tensile wave reaches point B, shown in Fig. 5(c), the difference between the tensile stress and the compressive stress is $0.24P$ $[P\times(1-26\%)\ -0.5P]$ which is larger than $0.2P$ again, and therefore, the second group of tensile failure zone around point B will be observed.

Similarly as the reflected tensile wave reaches point C, the tensile stress will be $0.23P$ $[P\times(1-2\times26\%)\ -\ 0.25P]$, and as it reaches point D, the tensile stress will be $0.22P$ $[P\times(1\ -3\times\ 26\%)]$.

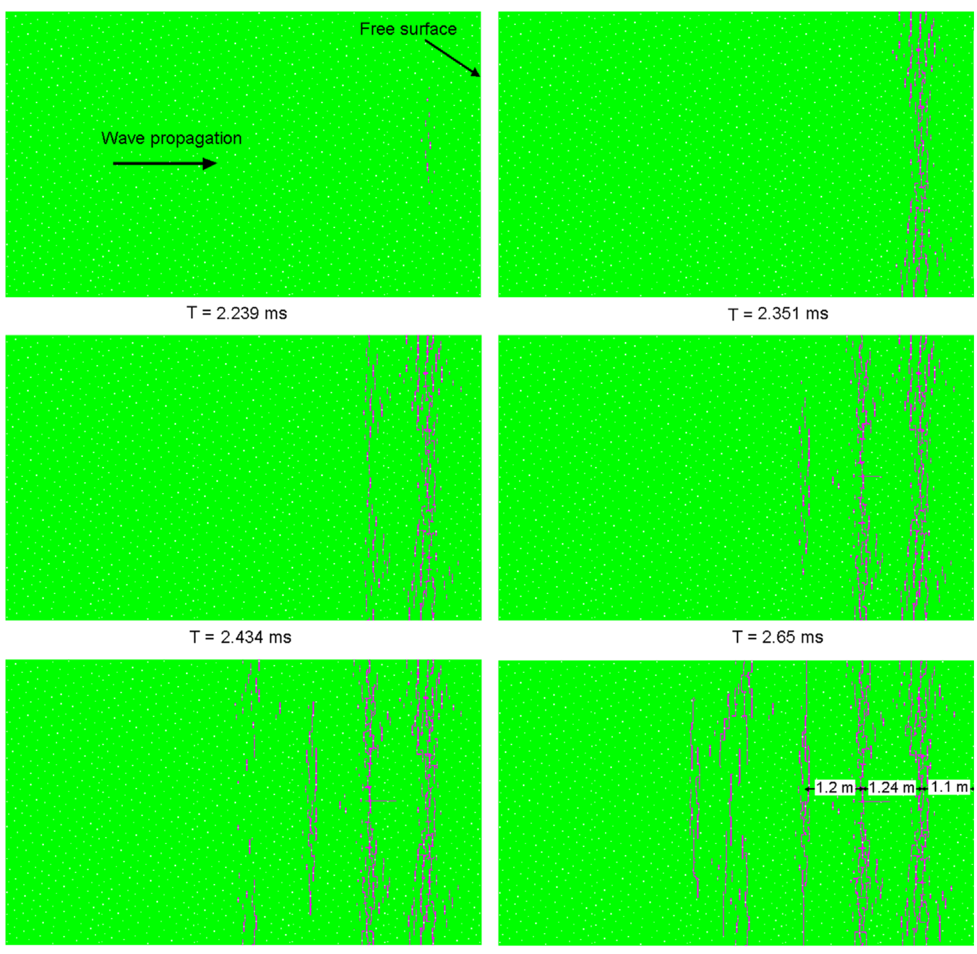

Fig. 8. The process of zonal disintegration around a working face as a function of time after the impact from the steel plate with a pressure of 51.5 MPa by using the model shown in Fig. 6.

Therefore, around both points C and D as shown in Fig. 5(d) and (e), a group of cracks will occur. From the above analysis, it can be seen that a slowly unloading P-wave can cause zonal disintegration as it encounters a free surface.

3. Numerical simulation

In order to confirm the above result about zonal disintegration, the dynamic finite difference method is applied, and the corresponding AUTODYN code is employed.

3.1. Numerical model

In this study, two 2D numerical models as shown in Fig. 6 are established. The models are treated as plane strain problem, and the right end is a working face in Fig. 6(a) or is a stope in Fig. 6(b). The top and bottom (dashed lines) of the models are treated as transmitting boundaries in which stress waves are not allowed to reflect back. The length unit in the models could be mm, cm and m.

The rock material in the models contains randomly distributed defects, including voids and pores, but in order to simplify the numerical models, cracks and joints are not considered. In Fig. 6, the defects consist of a number of void elements, and the ratio of total defect area to the area of the rock model is 1.0%. The defects actually consist of void spaces situated inside the target rock, so the defects have small free surfaces. Therefore, the borders of the defects are treated as free boundary, which means that as stress waves encounter defects, they will suffer reflection. The parameters of the target rock are summarized in Fig. 6.

In order to produce a slowly unloading P-wave, a steel plate with a proper speed V is employed as a projectile to impact the target rock, and the interaction between them will last for a long time so as to produce a slowly unloading P-wave. Fig. 7 shows the curve of pressure versus time recorded from a point near the touching edge of the target rock. It can be seen that the P-wave produced from the impact is a slowly unloading P-wave.

A modified principal stress failure criterion is applied in the determination of material status. When the major principal stress or the maximum shear stress in an element exceeds material tensile or shear strength, the element fails, that is

$$\sigma_1 \leq \sigma_T \quad \text{and} \quad \tau_{max} = \frac{\sigma_1 - \sigma_3}{2} \leq \tau_C \tag{1}$$

where σ_1 and σ_3 are the major principal stress and the minor principal stress, respectively, τ_{max} is the maximum shear stress, σ_T and τ_C are material dynamic tensile strength and dynamic shear strength, respectively.

3.2. Simulation results and analysis

In order to confirm the theoretical result of the mechanism of zonal disintegration presented in this paper, numerical simulations are implemented by employing the above numerical models, shown in Fig. 6, and AUTODYN code. It is shown that as the speed V of the steel plate is in a certain range, one may observe the curious phenomenon of zonal disintegration. Figs. 8 and 9 show the simulation result of the process of zonal disintegration around an excavation as a function of time. The right side of the model in Fig. 8 is a working face, i.e. a free face, and in Fig. 9, it is a stope boundary. Therefore, as stress waves reach there, they will reflect back, inducing

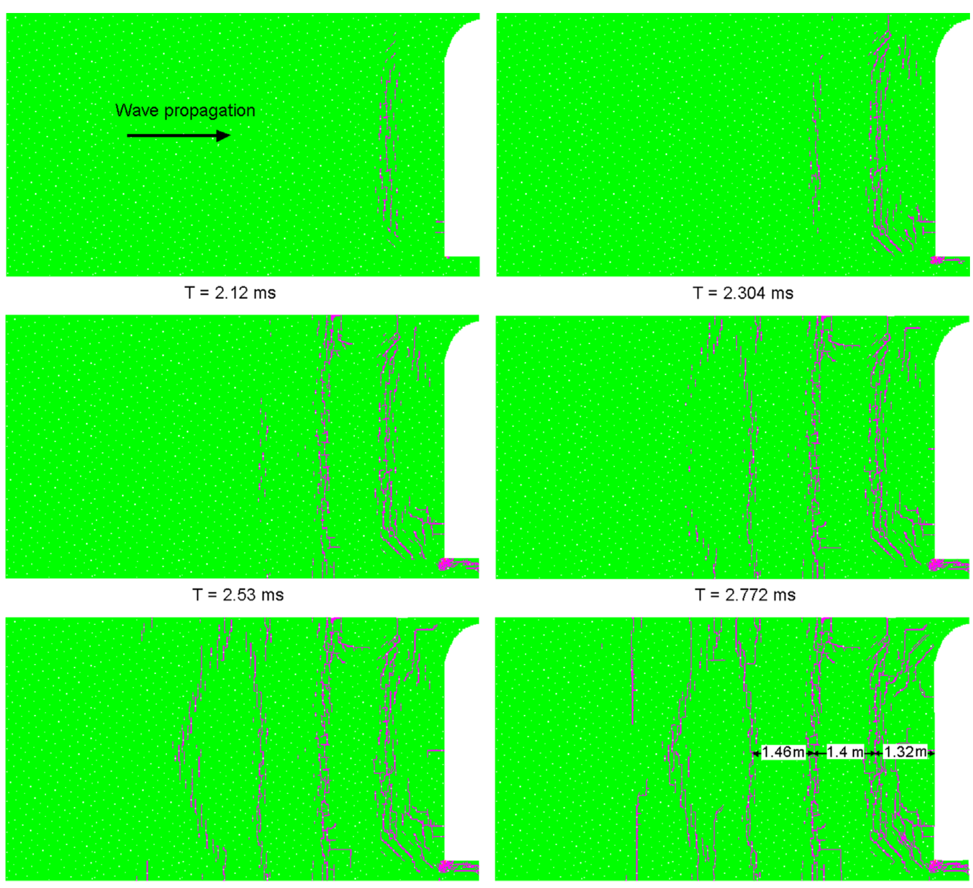

Fig. 9. The process of zonal disintegration around a stope as a function of time after the impact from the steel plate with a pressure of 51.5 MPa by using the model shown in Fig. 6.

tensile stresses, and the tensile stress will superpose with the compressive stress. As the difference is larger than rock tensile strength, the rock will fail and accordingly cracks will occur.

In order to demonstrate the reflected tensile stress waves as well as their function on zonal disintegration, five points as shown in Fig. 10 are selected to record their stress σ_x histories. It can be seen that three target points, i.e. points 1, 2 and 4, are just situated inside the three cracked layers, and their distances to the free surface are 349 cm, 231 cm, and 113 cm, respectively. From Fig. 10(b), one can find that all the three elements containing the points 1, 2 and 4 are failed by the reflected tensile stresses.

Fig. 10(c) shows that the stress history curve of point 5 is different from those of other points. This is to be expected as point 5 is near the free surface, and the reflected tensile wave will superpose with the compressive wave, and accordingly the element containing point 5 will not have a chance to fail by the tensile stress.

Point 4 is 72 cm from point 5, and as the reflected tensile wave travels to point 4, the tensile stress is larger than the compressive stress, and their difference is larger than rock material tensile strength of 27.7 MPa. Therefore, the element containing point 4 is failed by the tensile stress, and similarly, the failure occurs at points 1 and 2.

Point 3 is located between point 2 and point 4, and the element containing point 3 is not failed. This is because after the first cracked layer, the tensile stress wave amplitude will reduce because in the cracked zone, the cracks will open, which will result in the release of the tensile stress. Therefore, the tensile stress near point 3 is not large enough to produce new cracks.

3.3. Effect of the strength of slowly unloading P-wave

In order to investigate the effect of the strength of slowly unloading P-waves, the steel plate in Fig. 6 is designed with various speeds to impact the target rock because the impacting pressure is proportional to the steel impacting speed. Fig. 11 presents some of the simulation results. The results show that as the maximum pressure induced by the impact is less than 19 MPa (the impacting speed V is less than 1.6 m/s), no cracks occur in the whole rock model, and as the maximum pressure is larger than 19 MPa and less than 24 MPa (1.6 m/s < V < 2.0 m/s), although cracks can be observed, no zonal disintegration phenomenon occurs. As the maximum pressure is in the range between 35 MPa and 129 MPa (3.0 m/s < V < 11 m/s), zonal disintegration phenomena can be observed, and as it is larger than 140 MPa (12 m/s), a large number cracks occur, and since the damage is too serious, no zonal disintegration phenomenon can be clearly observed.

3.4. Effect of the porosity of rock material

Usually the natural rock is porous material, and therefore, in the numerical simulation, the models should contain defects. If the rock model shown in Fig. 6 does not contain defects, although under the same conditions, the phenomenon of zonal disintegration cannot be

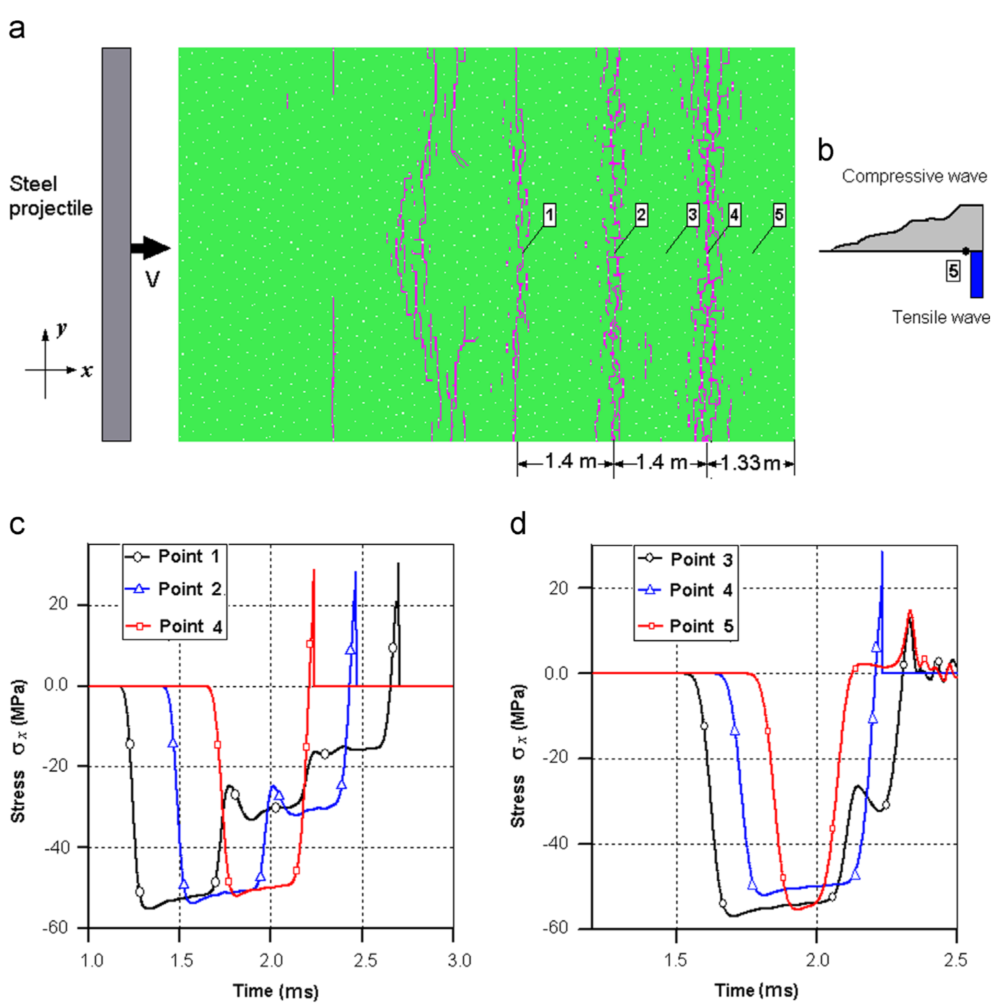

Fig. 10. Stress σ_x histories of five target points selected.

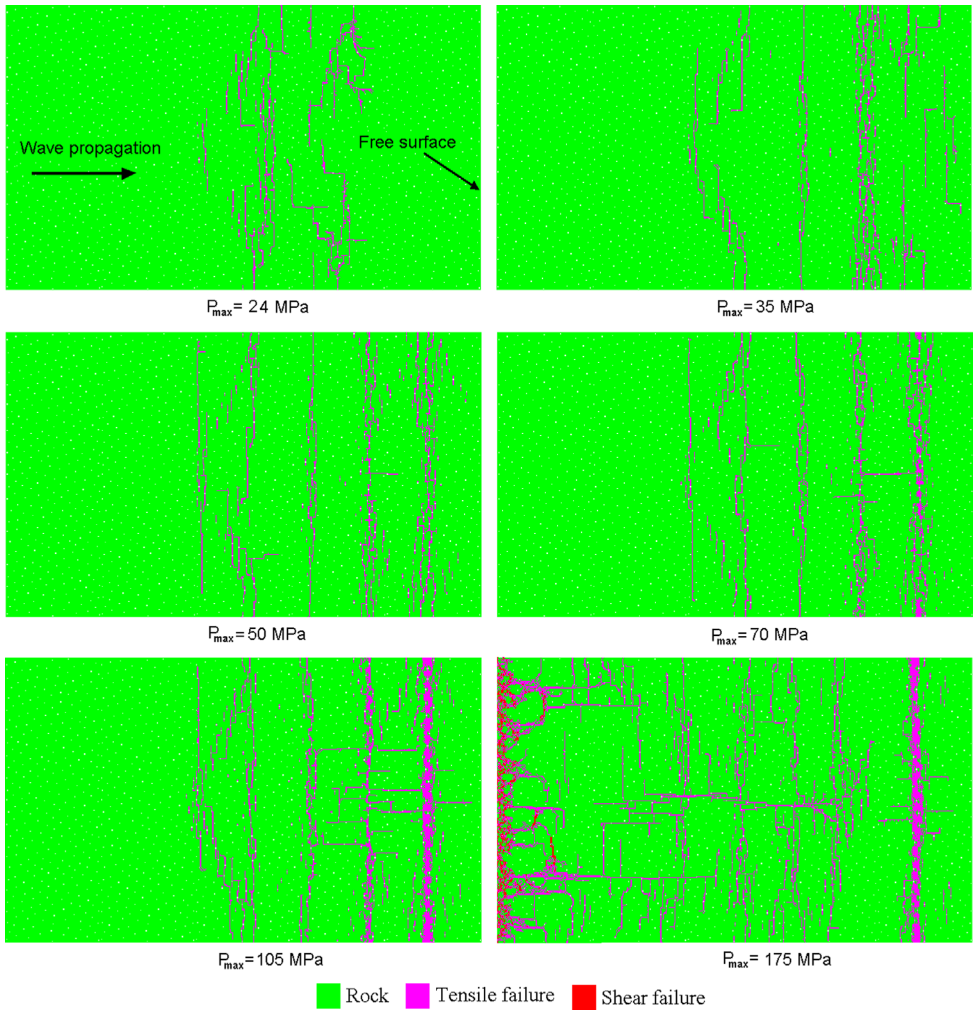

Fig. 11. The failure patterns near a free surface for different impacting pressures from the steel plate obtained by using the model shown in Fig. 6.

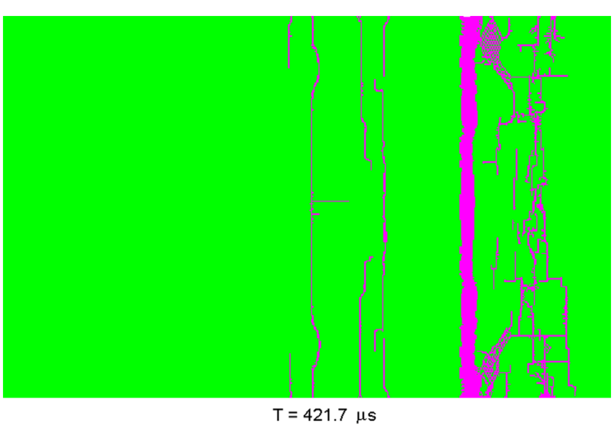

Fig. 12. The failure pattern for the rock model without defects under the same conditions as the model shown in Fig. 8.

clearly observed in Fig. 12. After the first major crack, several cracks occur, but no cracked zones are developed.

3.5. *Quickly unloading P-waves cannot induce zonal disintegration*

In order to further understand the mechanism of zonal disintegration, we let the interaction between the steel plate and the target rock stop just after the rectangle wave as shown in Fig. 13. It can be seen that under the rectangle stress wave (the other

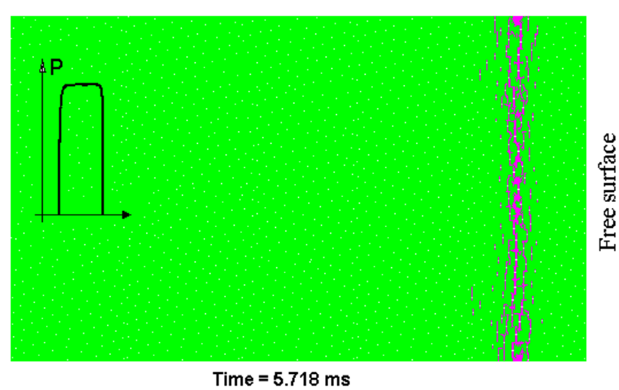

Fig. 13. The failure pattern of the surrounding rock under a rectangular incident wave.

parameters of the numerical model are the same as those shown in Fig. 8), near the free surface, only one cracked zone can be observed. This indicates that only slowly unloading P-waves can induce the phenomenon of zonal disintegration.

4. Discussion about the depth effect on zonal disintegration

In-situ observations showed that most zonal disintegration phenomena exist in deep mines, and in shallow places, they were rarely observed. As is well known, the confining stresses increase with depth [28,29], and thus the rock density ρ as well as the wave speed c will increase with depths. The stress σ induced by stress waves generally can be calculated by

$$\sigma = \rho c U_P \tag{2}$$

where U_P is particle velocity. From Eq. (2), one can find that the stress induced by stress waves increases with depths as both ρ and c increase with depths. Supposing both ρ and c increase by 10%, then the corresponding stress induced by the stress wave will increase by 21%. This indicates that in a deep area, a seismic P-wave will induce a larger stress which equivalently increases the seismic P-wave strength; thus the strength requirement discussed in Section 3.3 may be satisfied, and accordingly the phenomenon of zonal disintegration may occur near a free surface, whereas in a shallow area, the stress induced by seismic P-waves may not be strong enough to produce new cracks in the surrounding rock of an excavation. That is why zonal disintegration usually happens in deep areas.

5. Conclusions

Slowly unloading P-waves could be induced by an earthquake or an impact between two materials as their impacting action can last for a long time. The analysis on the process of a slowly unloading P-wave inducing the phenomenon of zonal disintegration has been implemented, and two defected rock models around an excavation have been developed. The investigation results show that:

(1) A slowly unloading P-wave could cause the phenomenon of zonal disintegration when it encounters a free surface.
(2) If the strength of a slowly unloading P-wave is too small, it cannot induce cracking, and if it is too large, the damage is too serious and one cannot clearly observe the alternately distributed cracked zones. From this simulation, it can be seen that for the rock concerned here (the parameters are shown in Fig. 6), when the maximum pressure of a slowly unlading P-wave is in the range between 35 MPa and 129 MPa, it could cause the phenomenon of zonal disintegration as it encounters a free surface, such as a stope or a working face.
(3) The natural rock usually is a porous material; thus in numerical simulations, rock models should contain defects. For the rock model without defects, the phenomenon of zonal disintegration cannot be observed. Therefore, using the porous rock model is necessary in rock numerical simulations, especially for high porous rock materials, such as sandstone.
(4) If the incident wave is not a slowly unloading P-wave, such as a rectangle wave, one cannot observe the phenomenon of zonal disintegration.

Acknowledgments

This work was financially supported by the Open Fund of State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (PLN1202), by the National Natural Science Foundation of China (51074109), and by the Major State Basic Research Project (2010CB732005).

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