陈卫忠[1,2]，吕森鹏[1]，郭小红[2]，乔春江[3]
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3. + B C D E F G H I 2 3 . J K D L 5 6 7 / 0 430056)

M # N O P Q R 1 S Q T % & U V W X Y Z [ \ 1 ] ^ _ ` a Q T % & U V W X b c 5 U d e f g h i # j k l m n o p W q r s t u T v w n v x l m W y z { | 5 2 3 e # } ~ • [ ! & " # $ e % & ' b ( ) * 5 + , e # N # } [ - . ~ • b ( / # N . 0 1 ' 1 2 _ { | = 3 4 5 M 6 7 O v w 8 O v x W y z 5 P Q R 1 T h i # 9 4 ] f g ~ • b ( 5 v w W y z : # ; 4 ] < [ f g = v x W y z > ? @ A 8 W q r s B C 5 # } f g ~ • B @ 5 & Z # N [ D E g B ; _ { | 2 3 0 3 F Q T % & # N & Z [ 1 G 2 3 / H I J K e { | L M _

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MN O P (1968 Q ) 5 2 3 R 5 S T Z U V 5 W X Q T % & Y Z [ - 2 < [ ' % \ E-mail: wzchen@whrsm.ac.cn

# Unloading confining pressure for brittle rock and mechanism of rock burst

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**Abstract**: Rock burst is often met in excavation unloading of underground engineering in high geo-stress areas. According to the actual stress state on surrounding rock, conventional triaxial and unloading confining stress laboratory tests are conducted for brittle rock during pre-peak strength and post-peak strength. The full-regime of the rock failure is analyzed and the characteristics of acoustic emission in the process of rock failure are studied. The rock deformation-failure characteristics and the mechanical mechanism of the rock burst are discussed. The test results show that the rock samples all exhibit brittle failures in pre-peak and post-peak unloading confining tests and the brittle characteristics in the pre-peak tests are stronger than those in the post-peak tests. The brittle failures of rock are more intensive with high unloading rate, and the probability of rock burst is larger. The characteristics of the rock burst are summarized. These results are helpful to the researches on the mechanical mechanism of rock burst.

**Key words**: mechanism of rock burst; unloading; triaxial test; deformation; failure mechanism

## 0

P R 1 t u T [ ] ^ n f g # _ ' U V a \ U b # _ c d e [ f g R - E [ g h i j 5 # } k l n f ' m n o p ] ^ [ q r \ 1 s t _ ! u F # N [ # } 1 ' { | 2 3 q v 9 w x y X { | Y z 5 { < # N & Z : [ R 1 ! & " o | } 5 ~ ¤ % & # _ U V ! & + J W z J y z 5 y W z ! & p : = } U d { | 2 3 5 2 3 0 3 > J U _

# _ W q / y q t u O r o p [ R 1 E 5 # _ 4 ] < [ 1 ' b g J S _ # } 1 ' 2 3 [ 5 B B 2 3 # _ ~ ¤ T [ - . < ~ •[1-9] 5 # } W q t u T - . ~ • [ { | 2 3 ; # d[10-16] _

h i # ? 2 3 F ^ 5 U d o p y z n o p W q r s t u T v w / v x W y z { | 5 2 3 W y z [ @ / - . b g " # $ % & ' b ( ) * _

## 1

### 1.1

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- ' 40772184 5 50720135906
2009 Q 01 Q 08

{ | w x + , - ' . / 0 # $ 1 ' 2 3 4 [
MTS 2 g { | 1 _ % & ’ w
w x DISP % & ’ I { 5 D F % & ’ X u
\ I n e d 5 ~ ] % & ’ [ ~ : I _

1.2

? 2 3 h i # o p y z T [ v @ 5
! o p y z [ j k l m { | v @ 5 U d v
w W y z { | 5 T 3 r . z M m P z a $s_1$ / o s - 5 P a/s [ r s W 2 T D ( 3 ) T j / F 1 +
0.1 MPa/s / 0.5 MPa/s [ r s W y z $s_3$ 8 W y
z $s_3$ [ p : o p r s y m z $s_1$ 8 m -
. o - W y z _

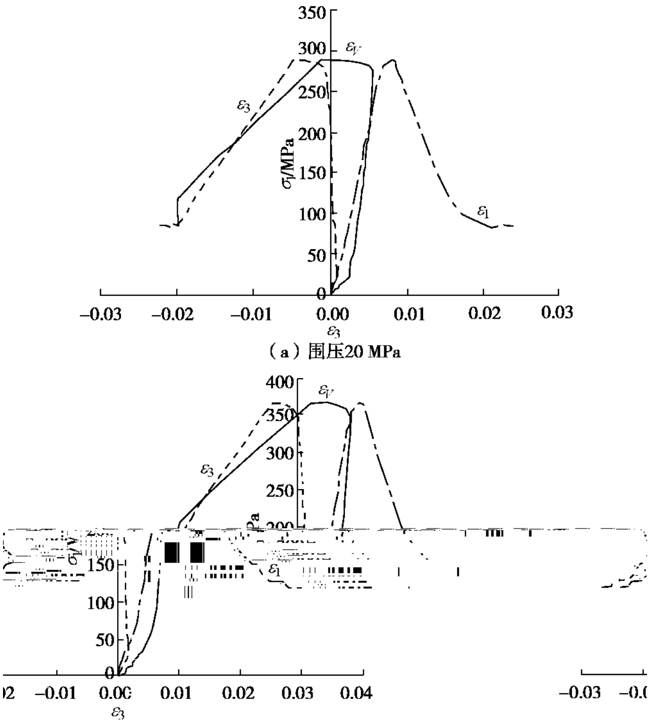
## 2

2.1

1

2 W y z $s_3$ 5 $s_1$ y

W y z r s T 0.1 MPa/s / 0.5 MPa/s : 5 W y z y m z [ { | = 3 < 4/55 y z W q : 5 $s_1$ g h T 5 = 5 # ; > ? u @ q E 1 5 ( ~ • A B O C : & Z [ 8 # ; ~ • : Y Z f [ ~ ! % _ = $s_1$ o - W y z ~ • > y @ A 5 ( $s_3$ [ 6 7 W q ; $s_1$ o - [ 6 7 5 = 5 y $s_1$ > D & Z ~ • 5 { < E F U V G H I $s_3$ J K n $s_1$ y L M N 5 O D & Z # N _

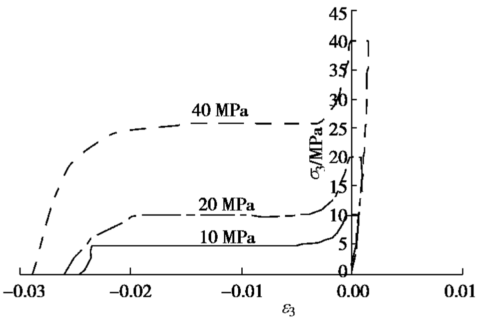



（a）围压20 MPa

（b）围压40 MPa

4 $s_1$ 0.1 MPa/s

Fig. 4 Curves of pre-peak unloading confining pressure with increasing $s_1$




5

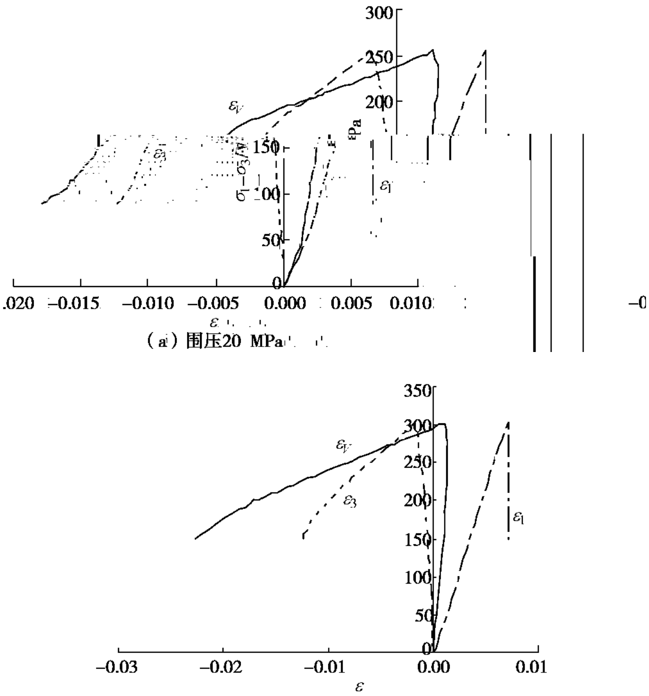
Fig. 5 Curves of confining pressure circumferential strain

3 m P Q o - W y z

W 6/7D R < W y z [ # $ % 5 # ; [ - . y o ; 5 ( - . / y z ) " * g + 5 4 5 # ; [ - . ) O f g - . _

y z [ 3 5 # ; < ] 0 g - . _

W y z ! & m R 1 [ - S 5 T U V * 5 # ; [ m R 1 $s_1$ W y z [ 3 : o X 3 5 # ; @ 3 8 _ y z 3 Y m R 1 3 # ; ~ ¤ @ q [ m R 1 : 5 # ; & Z ~ • 5 & Z ; Z [ R 1 _ 94 [ 5 = 5 y z F m @ q E 1 [ \ ! O ] ^ [ _




（a）围压20 MPa

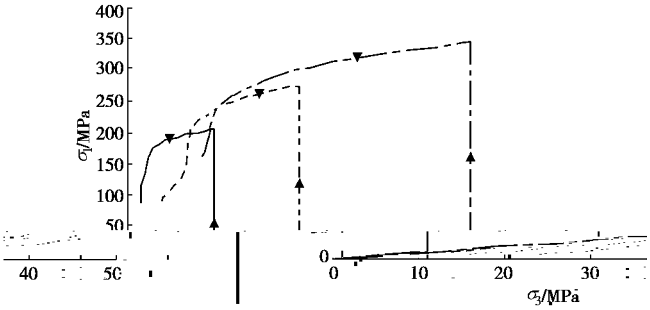
（b）围压40 MPa

6 $e_1$

Fig. 6 Curves of pre-peak unloading confining pressure with constant

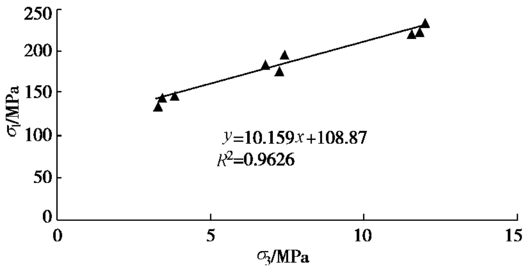
yc (g)51 10.56 Tf 0-0.24 T10464Tj -0.Ir

j # d e [ f g R - E F k i j _ { O = 5 3 F # _ l m J n [ o p L y z 5 d e j # i j [ E i q r ? ~ # s [ \ E 5 # : D E t u v w # N _




8

Fig. 8 Complete curves of axial stress-confining pressure

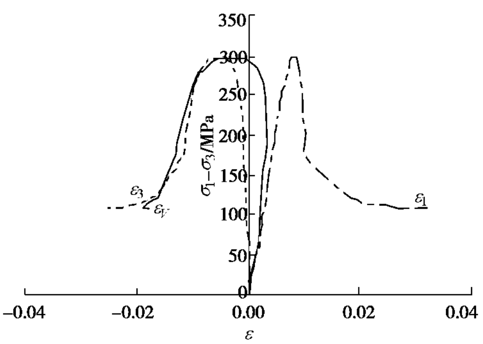



9

Fig. 9 Curves of axial stress-confining pressure

2.2

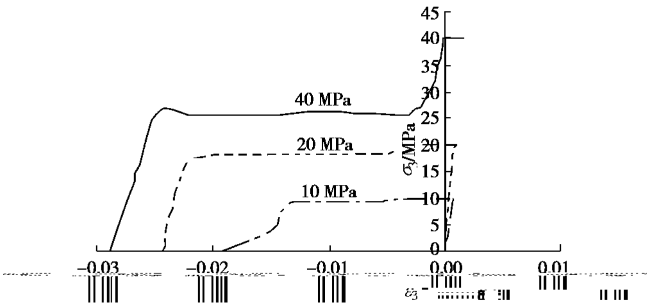
v x W y z { | x y R 1 R - + z * 10 { 12 4 [ _ { | = 3 4 5 M y z B ; 5 $s_1$ - $s_3$ o - [ | } T 5 W y z x m R - z * B ~ • ! 5 = 5 y z B ; 5 # } W y z x f g B o 5 _ W y z " w 5 { ; # < ] $ 5 W y z Y # ; $ % & y r 5 Y Z ^ [ _ ' % & n R _ = 5 { ; c # < ] 5 [ ~ Z 5 Y c E i # ( i j _ { O y z B ; 5 # } v x W y z f g B o 5 [ j ' _ W y z " w 5 m - . # & Z 0 g - . 5 R 1 R - z * o v w W y z { | d ; ) j • N G * f f g + y 5 y z [ ; 5 { r ] ^ , y 5 _




（a）围压20 MPa

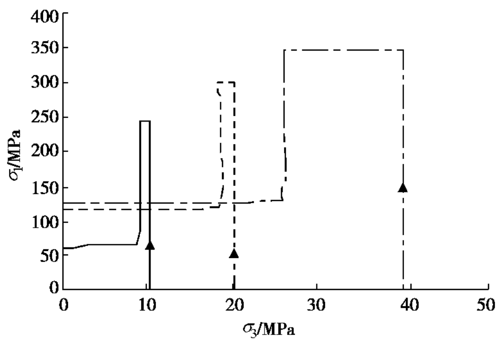
10

Fig. 10 Curves of post-peak unloading confining pressure




11

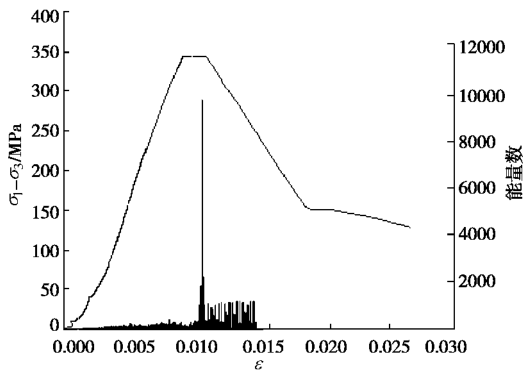
Fig. 11 Complete curves of confining pressure circumferential strain



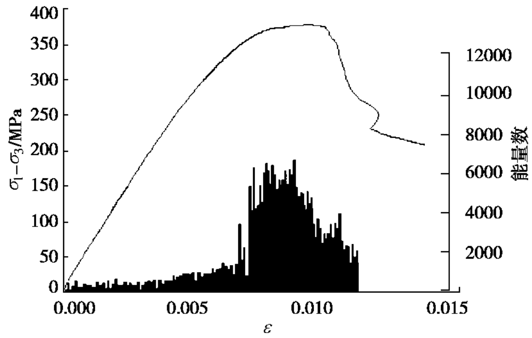

12

Fig. 12 Complete curves of axial stress-confining pressure

v w W y z < v x W y z y z 9 O 40 MPa n W q r s ? 0.1 MPa/s % & ' F = 5 13 4 [ _




（a）峰前卸围压




（b）峰后卸围压

13

Fig. 13 Comparison of acoustic emission

vwWyz Wqw%&’Ei ]K5 ~• :> y5#}{;4]?5 [fg~•8vx Wyz{|+5W Wqw{;#-. v @ 5 ,:{;#-<]~ Z5%&’Ei -;5Wq x67~•:Ei "/J5 y5fg~•b( /JvwWyz@A_

{|=0x1#;W23456+ <:D R {;4Z7•JWXkl[8gl95{=5vx Wyz!&+WX:{; <] ?5 [~ Z5 #;~•o vwWyzdehA5 14 4[5{ OW #<][~ SY{;4deEiJ4ij[ =35: #;e q89;<8#;[=>?~• Z5@A #;B=>?Z"k8e mi[C > ?~•Z5"(#;Dm e L i[!$ m R1EY [F Z5{;4]<8>g~•[b (_

}dclmWyz#}1'{|5e?#N&Z!& OEi'fQij[!&5M,D)?MEi'fn g 4.0< dn 49 <N _

1 Ei'f

EFUVw5#_ l R1!h T5I z4 5deJ;i[fgR-E_EFUV5 #_ R1iBn#_ j0JK5#_D Y EFc&ZQ\5@W y#CkR1)l5 m O? R1 y5 ny#D EF&ZP Q[j0oR1 +5C Ei y_

2 g 4.0< d

#}c e ;i[glp5W UVWX5y #R1&Z )P5 4[qoR1&ZP +5 qo[ +R1; #}[rs~•@ 5g 4 d5p:ijR-E5 ij< [fgR-E; .0 [g 44t[Ei5g 4&Zou d_ g 4[oX d n.0 [g 45v •g 4LU5~9 _v•g 4LU9 5.0 wa)[ 4_

3 49

4oX d ;56x9;_#N&Z5[ \[fgR-EqS?\E5Y~ [#s kln opnf';op[x\YzyUz__

{k5#N[&Z<Wyz[rs4?L+_ QTGdUV:5qkUV[# ,;5ij[E i ,;8UV[rs,P5Eiijrs ,P_ m UVZwY~•-.o52Z:5UVZ< -.o52Z"G[R1>y +5R-E;if

|"G5y#R-E y5: OKed E} 35,:5~Jo• DEUbUVZ<- .o52Z"G[#}~ 5mn ko<5.0 #N_', !Q<!%r 5= JmqkUV [# 5w|wx}G[!%("5D J&w 3#N[&Z_

## 4

1 Wyz> DUb#}&Z~ 5 ~•& >?@A5(#;~•4]<[fgvwWyz =vxWyz>@A_

2 #;yq~•Ogh{|1[Ei5:Wy z~•67Ovw8OvxWyz5{u9O ! aijEi~][5"(Wq~•#;ij[E1K yq~•#;de[Ei_

3 Wyzrs C:5 #[$%/R1[q Qo&)567@qE1B;5@W Ei o & )[ij5 ~•:ij[EiB;5fg~•B5 5~•@ B;_ QT%&[!%UV!&+5 D !Q<!%r 5 2y#[PQ J&w 3#N[&Z_

4 y$s_1$:Wyz=$s_1$ o-Wyz=~ •>y@A5($s_3$[67Wq ; $s_1$o-[6 7 5=5 y$s_1$> D~•5{<EFUVGHI $s_3$JKn$s_1$ yMN5O D&Z#N_

5 vxWyz#}fgo5 _Wyz"w5 {; #<]$ 5WyzY #;$ %&y r5YZ ^[_'%&nR_=5{;c #<] 5 [~ Z5Yc Ei #(ij5#;~ •o vwWyzdehA_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