! " # $ % & ' ( ) * + , - . / 0 1

1 2

(1. + , - . / 0 1 2 3 4 5 6 7 8 9 : ; 610051 < 2. = > ? ' # $ % & @ ' A B C 7 D E F G 210098)

2 3 4 H I J # K L M N O P Q R S # T L M U V P R Q R S W X Y L M Z U 7 [\ ] ^ 1 W X Y L M _ ` S a b c 7 d e f g h i S W X Y j k L M l m 5 n 7 o 5 n p q r s # K t u v w x y z L M S { | } ~ • 7 # K U v L J 7 A B I J # K v L S l m j 7 k R S Q R X 7 H # K O k R l m L M } • 7 v S l m & 7 l m f A B : S J R } 5 6 7 4 I J # K < k R < L M < v L J 8 9 : ; < 4 TU43 = > ? @ A 4 A = B C < 4 1000 D 4548(2010)06 D 0908 D 08 E F G H 4 @ (1973) 7 7 = 7 7 % & 7 # w ' - - . % & Y S A B }

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Orthotropic equivalent deformation parameters of jointed rock mass

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Abstract: The deformation of rock mass is considered as the summation of the linear elastic deformation of intact rock block and nonlinear elastic deformation of joints. On the basis of deformation characteristics of joints, a new constitutive model for normal displacement of joints is presented. It considers the influence of the initial stress state on the deformation. The computation method for jointed rock mass equivalent strain is studied by use of the joint network and the theory of equivalent continuous strain. According to the elastic orthotropic constitutive model, the rock mass is regarded as orthotropic continuous material, and the orthotropic equivalent deformation parameters are computed. The computation codes of orthotropic equivalent deformation parameters are developed. The example verification is carried out to test the rationality of the analytic results and the codes.

Key words: jointed rock mass; orthogonal anisotropy; equivalent deformation parameter; theory of equivalent continuous strain

0 I J

I J # K [S z L M _ R 1 { | } # K w ' A B : 7 # K L M # K L M # T L M U # K W X L M I J U S / / \ : 7 # K W X L M g ? # K S L M [1-2] } I J 7 \ \ 7 [# K % & \ ] 7 z g I J \ ] p S } 7 \ # K S ^ 7 @ ' J S j H # K : O K L M 7 # K % & \ ] S 1 j } # K L M S j 1 j \ ] j \ ] j R \ ] j \ ] j } j U \ ] j a

: 7 W # K 7 o j 1 ? S R 7 [1-5] < \ ] j # K q % & O a b [6-7] < R \ ] j a J l m # K 7 J A B [8-9] < j r s : U t u v w { | # K S 7 S # K 7 l m ? # K # K L M 7 o j 1 S _ ` 7) 1 ' [10-13] S N } [W 1 W X Y L M X S a b

K K K K K K K

L M N O 4 ` a b A B 0 973 2002CB412707 < ~ @ ' a 50539110

P Q R S 4 2009 03 13

c 7 d e f g h i S W X Y j k l m 5 n } ~ • 7
K U v L J 7 H # K L M
N O P Q R S # T L M U V P R Q R S W X Y L M Z
U 7 A B f # K v L l m j } • 7
k R X 7H # K O k R K 7
d e f # K k L M S l m j }

1 ! " # * + T , U V

1.1 * + W X T , L Y ! Z

K S L M O # T L M k 7U W X Y L M e^{J}
\ Z U

$$e = e^{R} + e^{J} \quad \} \tag{1}$$

T S v L e^{R} P Q R X l m < W X Y S
v L e^{J} n l m [14-15]

J J $\frac{1}{2}\left(\quad\right)d$

Z ; S z : . 7 K_{n}^{q} U K_{s}^{q} : ? 7 W X Y S j k 9 v w < ? g S = 7 W X Y L M v > ? 7 W X Y @ 0 < A W X Y S K_{n}^{q} U K_{s}^{q} W X Y B 9 C D E W X Y # K t u v w x y t u / h 1 7 1 V P R U R }

2 W X Y j k l m # K W X Y L M _ ` \ ] 7 F # K [G H - 9 w hs_{c}^{R} = 7 W X Y I J = 7 $d_{n}^{q}=d_{s}^{q}=0$ 7 $K_{n}^{q}=+$ K 7 H j k 6 O

$$K_{n}^{q}=\frac{K_{n0}^{q}}{\left(\frac{s_{n}^{q}-hs_{c}^{R}}{hs_{c}^{R}}\right)^{2}} \quad 7 \qquad (8)$$

n 7 s_{c}^{R} O I # T B 9 C 9 v w 7 L 4 7 (1 0) O M N 7 K_{n0}^{q} O t u j k 6 } H n 8 ( ) n 7 S g n 7 O \ 7 r s $s_{n}^{q}=hs_{c}^{R}$ = 7$d_{n}^{q}=0$ S P 7 * s_{n}^{q} hs_{c}^{R} = S j k l m 5 n

$$d_{n}^{q}=\frac{\left(s_{n}^{q}-hs_{c}^{R}\right)^{3}}{3K_{n0}^{q}\left(hs_{c}^{R}\right)^{2}} \quad \} \qquad (9)$$

s_{n}^{q} hs_{c}^{R} = ' W X Y S 9 v w Q hs_{c}^{R} = 7 $d_{n}^{q}=0$ }

^ t u j k v w s_{n}^{0} R W X Y t u / d_{n}^{0} = 7 n 9 p q

f

S v w U v L L $ O $\vec{N}_1$-$\vec{N}_2$-$\vec{N}_3$ v w U v L

$$\left.\begin{aligned}[s_{ij}]_{123}&=[H][s_{ij}]_{XYZ}[H]^{\mathrm{T}}\ 7\\ [e_{ij}]_{123}&=[H][e_{ij}]_{XYZ}[H]^{\mathrm{T}}\ 7\end{aligned}\right\} \tag{16}$$

n $[H]=\begin{bmatrix} l_1 & m_1 & n_1\\ l_2 & m_2 & n_2\\ l_3 & m_3 & n_3\end{bmatrix}$ 7 [*H*] O L $ % & 7

$[s_{ij}]_{XYZ}$ U $[e_{ij}]_{XYZ}$ O X-Y-Z S v w U v L } L $ % & [*H*] p q 3 L $ *!* 7 " U #

$$\left.\begin{aligned} l_1&=\cos a\sin b\cos g+\cos b\sin g\ 7\\ m_1&=\cos a\cos b\cos g-\sin b\sin g\ 7\\ n_1&=-\sin a\cos g\ 7\\ l_2&=\cos a\sin b\sin g-\cos b\cos g\ 7\\ m_2&=\cos a\cos b\sin g+\sin b\cos g\ 7\\ n_2&=-\sin a\sin g\ 7\\ l_3&=\sin a\sin b\ 7\\ m_3&=\sin a\cos b\ 7\\ n_3&=\cos a\ \}\end{aligned}\right\} \tag{17}$$

7 [*X-Y-Z* k R Q R X ` 9 L M U 3 L $ 12 _ 1 2 }

2.2 $ % & ' ( ) * + , - . / U V

1 # K L M l m [7 I # T L M k R S P Q R X l m 7 L M l m O # T S Q R *E* U a b c *m* < W X Y S L M v L J l m 7 H O k R L M 7 L M p q E_1^{J} 7 E_2^{J} 7 E_3^{J} 7 E_{12}^{J} 7 E_{23}^{J} 7 E_{31}^{J} 7 G_{12}^{J} 7 G_{23}^{J} 7 G_{13}^{J} 9 Q R L M U 3 L $ *!* 7 " U # 12 } k R S # T L M U k R S W X Y L M d e C * S # K L M f O k R L M 7 L M] $\vec{N}_1$-$\vec{N}_2$-$\vec{N}_3$ W X Y L M S 3 L M] 7 p q *!* 7 " U # 7 S k R L M n l m

$$\left.\begin{aligned} E_1&=\frac{E_1^{\mathrm{J}}E}{E_1^{\mathrm{J}}+E}\ 7\ E_2=\frac{E_2^{\mathrm{J}}E}{E_2^{\mathrm{J}}+E}\ 7\ E_3=\frac{E_3^{\mathrm{J}}E}{E_3^{\mathrm{J}}+E}\ 7\\ E_{12}&=\frac{E_{12}^{\mathrm{J}}E}{mE_{12}^{\mathrm{J}}+E}\ 7\ E_{23}=\frac{E_{23}^{\mathrm{J}}E}{mE_{23}^{\mathrm{J}}+E}\ 7\ E_{31}=\frac{E_{31}^{\mathrm{J}}E}{mE_{31}^{\mathrm{J}}+E}\ 7\\ G_{12}&=\frac{G_{12}^{\mathrm{J}}E}{2(1+m)G_{12}^{\mathrm{J}}+E}\ 7\ G_{23}=\frac{G_{23}^{\mathrm{J}}E}{2(1+m)G_{23}^{\mathrm{J}}+E}\ 7\\ G_{13}&=\frac{G_{13}^{\mathrm{J}}E}{2(1+m)G_{13}^{\mathrm{J}}+E}\ \}\end{aligned}\right\} \tag{18}$$

I # T S Q R *E* U a b c *m* p q . P 7 7 l m I J # K k R L M S + 7 [l m 1 2 W X Y k R L M S 9 L M R 3 L $ ' 3 L M] S k }

2 W X Y L M l m v L J l m W X Y k R L M R v L] S a g h O

a l m v w x y S v w s_1 7 s_2 U s_3

b v L] $\vec{N}_1$-$\vec{N}_2$-$\vec{N}_3$

H L $ *!* 7 " U # [L i j g < \ L O *n* 7 *m* U *n* L ` 7 L ` (*!*$_i$ 7 "$_j$ 7 #$_k$) z v g $\vec{N}_{1i}-\vec{N}_{2j}-\vec{N}_{3k}$ *i*=1 7 2 7 7 *n* < *j*=1 7 2 7 7 *n*" < *k*=1 7 2 7 7 *n*# } [7 \ k e v w s_1 7 s_2 U s_3 7 5 v w O 0 S v w 7 l m v S v L } k R X _ ` 7 [$n_!$ l $n_"$ l $n_\#$ 7 W X Y S v L] $\vec{N}_1$-$\vec{N}_2$-$\vec{N}_3$ p q m L O 3 5 v L n z Z U . S o }

c k R L M S & L *M* $\vec{N}_1-\vec{N}_2-\vec{N}_3$ S $\vec{N}_{1i}^{m}-\vec{N}_{2j}^{m}-\vec{N}_{3k}^{m}$ *m*=1, 2, 3, , *M* 7 H $\vec{N}_{1i}^{m}-\vec{N}_{2j}^{m}-\vec{N}_{3k}^{m}$ S v w s_{ijk}^{m} U v L e_{ijk}^{m} \ L $ O $\vec{N}_1-\vec{N}_2-\vec{N}_3$ v S v w $\overset{m}{}_{123}$

$$[A^m]=\begin{bmatrix} s_{11}-hs_c^R & 0 & 0 \\ 0 & s_{22}-hs_c^R & 0 \\ 0 & 0 & s_{33}-hs_c^R \\ hs_c^R-s_{22} & hs_c^R-s_{11} & 0 \\ 0 & hs_c^R-s_{33} & hs_c^R-s_{22} \\ hs_c^R-s_{33} & 0 & hs_c^R-s_{11} \end{bmatrix}^{(m)\mathrm{T}}$$

$$[X]=\left[\frac{1}{E_1^J}\quad\frac{1}{E_2^J}\quad\frac{1}{E_3^J}\quad\frac{1}{E_{12}^J}\quad\frac{1}{E_{23}^J}\quad\frac{1}{E_{31}^J}\right]^{\mathrm{T}}$$

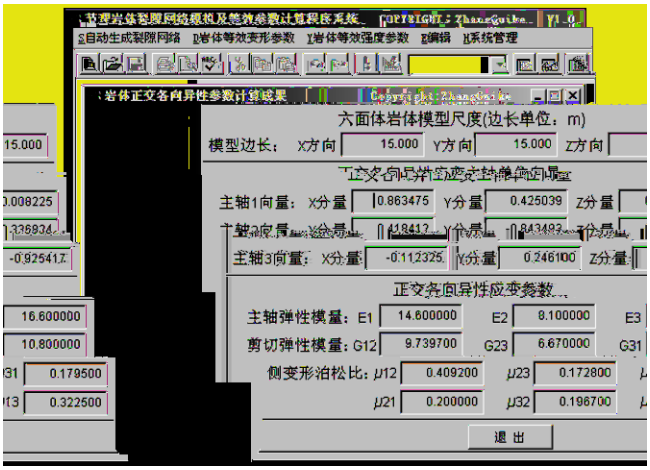
$$[D^m]=\left[e_{11}\quad e_{22}\quad e_{33}\right]^{(m)\mathrm{T}}$$

$$G=[G_{12}^J\quad G_{23}^J\quad G_{31}^J]=\frac{\sum_{m=1}^{M}G^m}{M} \qquad (21)$$

$$[A]_{3M\times 6}[X]=[D]_{3M\times 1} \qquad (22)$$

$$[A]_{3M\times 6}=\begin{bmatrix}[A^1]\\[A^2]\\ \cdots \\ [A^m]\\ \cdots \\ [A^M]\end{bmatrix}\quad [D]_{3M\times 1}=\begin{bmatrix}[D^1]\\[D^2]\\ \cdots \\ [D^m]\\ \cdots \\ [D^M]\end{bmatrix}$$

$$\left.\begin{aligned}\frac{m_{12}}{E_2}=\frac{m_{21}}{E_1}=\frac{1}{E_{12}}\\ \frac{m_{31}}{E_1}=\frac{m_{13}}{E_3}=\frac{1}{E_{31}}\\ \frac{m_{32}}{E_2}=\frac{m_{23}}{E_3}=\frac{1}{E_{23}}\end{aligned}\right\} \qquad (23)$$



9 3 * + , - . / m p o]

Fig. 3 Output interface for equivalent parameters of deformation

& l m : S L $ *!* 7 " U # S L ` *n* 7*n* U *n* R ' u [L • ; c S <) * d*E* *n* 7*n* U *n* S : ? 7d*E* : . 7 l m : : 7 9 l m A = : * }

4 V q r s

m S [24] C = : S 7 z # K k R l m & } m t u v w U t u n l m W X Y S 7 S [22-23] 7 m # K S t u v w O

$$\begin{cases} s_x^0 = -(4.3982 + 0.01186h) \text{ 7} \\ s_y^0 = -(4.7152 + 0.01207h) \text{ 7} \\ s_z^0 = -(1.6628 + 0.03039h) \text{ 7} \\ t_{xy}^0 = -(0.4050 + 0.00005h) \text{ 7} \\ t_{xz}^0 = -0.0472 + 0.00001h \text{ 7} \\ t_{yz}^0 = -0.747 + 0.00046h \text{ 7} \end{cases} \tag{25}$$

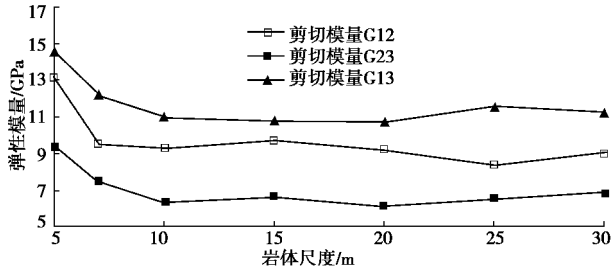
n v w O MPa 7 *h* O # K B C 7 O m } Y S t u j k O NNW 0.50 mm 7 NNE 0.21 mm 7 NEE 0.30 mm 7NWW 0.72 mm < t u k O 0 } W X Y S t u / 4 D \ 7 [= : = = : }

I # T S B 9 E 2 s_c^R =100 MPa 7 Q *E*=45 GPa 7 a b c *$*=0.17 7 =0.22 }

H c 2 >) l m & 7 \ L 5 77 710 715 7 20 7 25 U 30 m 7 S # K l m 7 l m 10 F 7L O o # K S k R L M 7 l m : @ 1 U 2 7 L M S L - G H @ 4 7 5 U 6 } S : \ ] p q I e # K

? 20 m • 7 # K S k R L M @ J 7 p q * e v # K S REV v ? I J Y ? K * " L 3 M S W } N S [24] S A B : g O }

t 1 $ % & ' ( ) * + , - . / U V u v



9 6 , - . / G_{12}, G_{23}, G_{13} { " # | } 5 ~

Fig. 6 Relationship between deformation parameters G_{12}, G_{23}, G_{13} and rock mass scale

5 [Z

K v L J k R Q R X U # K 7 A B f # K k R L M S l m j 7 o j p q J Y r s I # T L M W X Y L M R I J S { | } S A B : W 1

1 d e f g h i S W X Y j k l m }

2 P A B f I J # K S v L l m j }

3 d e f H # K O k R L M Q R K S j R v l m j }

4 I J # K S L M 1 Q S k R 7 L M R # K S < ? S T 7 # K S ? I J Y ? K * " L S 3 M = L M @ J 7 N f S [24] C d e S # K REV D S J R }

. • = > 4

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