Determination of Equivalent Mohr-Coulomb Criterion from Generalised Hoek-Brown Criterion

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Abstract

A new analytical solution is presented for determining equivalent Mohr-Coulomb (MC) shear strength parameters over an arbitrary interval of minor principal stress σ_3 from the generalised Hoek-Brown (HB) criterion using least squares method. Comparison with several published examples demonstrates that the proposed solution had a capacity to accurately determine equivalent MC parameters over a given interval of σ_3, as well as instantaneous MC parameters by using a very small interval of σ_3. EMC parameters depended heavily on the interval of σ_3, which highlighted the importance of intervals of σ_3. A calculation case shows that the equivalent internal friction angle and cohesion over the interval of σ_3 from tension cut-off $\sigma_{\text{cut-off}}$ to maximum minor principal stress $\sigma_{3\max}$ were approximately 12% smaller and 10.3% larger than those over an interval from tensile strength to $\sigma_{3\max}$, respectively. The proposed solution offers great flexibility for the application of the HB criterion with existing methods based on the MC criterion for rock engineering practice.

Keywords: equivalent Mohr-Coulomb parameter; Hoek-Brown criterion; least squares method; tensile strength

1 Introduction

The linear Mohr-Coulomb (MC) and nonlinear Hoek-Brown (HB) criteria are the most widely used failure criteria in slope stability analysis, and most of the currently used geotechnical codes are based on the application of the MC parameters. Consequently, it is necessary to convert the HB criterion to the MC criterion without significantly affecting the results of analysis. However, the HB criterion is expressed major and minor principal stresses σ_1 and σ_3, and its conversion to the relationship between shear strength τ_f and normal stress σ_n is not straightforward.

Generally, the HB failure envelope is replaced by a tangent line and instantaneous MC (IMC) parameters are determined by locating the tangent of the HB envelope at a specified σ_n. The nonlinearity of the HB criterion causes IMC parameters to vary with σ_3, consequently, the method theoretically yields the most accurate MC parameters but only for a specific stress state. An exact solution for intact rock was proposed by Hoek (1983), and IMC parameters can be obtained numerically for rock masses (Kumar 1998; Carranza-Torres 2004; Priest 2005; Yang and Yin 2006; Shen et al. 2012a; Lee and Pietruszczak 2017). Alternatively, another method provides equivalent MC (EMC) parameters by best fitting an averaged line equivalent to the HB criterion over an interval of σ_3. EMC parameters are more appropriate to evaluate the overall strength of rock mass, especially for preliminary design purposes. EMC parameters were determined by linear regression analysis for intact rock (Hoek and Brown, 1997) and rock masses (Hoek et al., 2002). Note that the solution proposed by Hoek et al. (2002) is valid only for the artificial interval from biaxial tensile strength σ_{t2} to maximum minor principal stress $\sigma_{3\max}$. No accurate analytical solution for determining EMC parameters over an arbitrary interval of σ_3 is available yet.

A new analytical solution was proposed to determine EMC parameters over an arbitrary interval of σ_3 using least squares method. The reliability and performance of the proposed method were verified based on several published examples. The importance of the intervals of σ_3 was highlighted by comparing EMC parameters over different intervals of σ_3.

2 Overview of the Equivalent Hoek-Brown and Mohr-Coulomb criteria

The HB failure criterion for intact and fractured rock masses was first proposed in 1980 to describe a nonlinear empirical relationship between σ_1 and σ_3. Since then, it has been widely accepted by the international rock mechanics, and updated several times in response to experience gained with its applications (Hoek and Brown 2019). The HB criterion in the latest version, often referred to as the generalised Hoek-Brown criterion, is expressed as (Hoek and Brown 1997):

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(\frac{m_b\sigma_3}{\sigma_{ci}} + s\right)^a \tag{1}$$

where, σ_1 and σ_3 are the major and minor principal stresses, and σ_{ci} is the uniaxial compressive strength of the intact rock mass. m_{b}, s, and a are the constants of the HB criterion. Hoek et al. (2002) proposed the following revised empirical expressions for m_{b}, s, and a.

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \tag{2}$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right) \tag{3}$$

$$a = \frac{1}{2} + \frac{1}{6}\left[\exp\left(-\frac{GSI}{15}\right) - \exp\left(-\frac{20}{3}\right)\right] \tag{4}$$

where GSI, m_{i}, and D is the Geological Strength Index, rock type-dependent parameter, and the disturbance factor, respectively.

The equations provided by Hoek et al. (2002) for determining EMC parameters over an artificial interval [σ_{t2}, $\sigma_{3\mathrm{max}}$] are:

$$\varphi = \arcsin\left(\frac{6am_b\left(\frac{m_b\sigma_{3\max}}{\sigma_{ci}} + s\right)^{a-1}}{2(2+a)(1+a) + 6am_b\left(\frac{m_b\sigma_{3\max}}{\sigma_{ci}} + s\right)^{a-1}}\right) \tag{5}$$

$$c = \frac{\sigma_{ci}\left[(1-a)\frac{m_b\sigma_{3\max}}{\sigma_{ci}} + (1+2a)s\right]\left(\frac{m_b\sigma_{3\max}}{\sigma_{ci}} + s\right)^{a-1}}{(2+a)(1+a)\sqrt{1 + \frac{6am_b\left(\frac{m_b\sigma_{3\max}}{\sigma_{ci}} + s\right)^{a-1}}{(2+a)(1+a)}}} \tag{6}$$

Note that the value of $\sigma_{3\mathrm{max}}$ has to be determined for each case. Hoek et al. (2002) suggested empirical formulae to determine the value of $\sigma_{3\mathrm{max}}$ for deep tunnels and slopes, respectively.

3 Proposed solution to determine EMC parameters

A new analytical solution was formulated by least squares approximation to determine EMC parameters over an arbitrary interval of σ_3, of which the lower limit is not necessary to be σ_{t2}. That is, for an arbitrary interval of σ_3 defined by [σ_{3a}, σ_{3b}], we search for a best linear approximation expressed as the MC criterion of the generalised HB criterion in the sense of least squares, as illustrated in **Fig. 1**.

The generalised HB is expressed as

$$\sigma_{1\mathrm{HB}} = \sigma_3 + \sigma_{ci}\left(\frac{m_b\sigma_3}{\sigma_{ci}} + s\right)^a \tag{7}$$

where $\sigma_{1\mathrm{HB}}$ is the major principal stress of the HB criterion.

The equivalent MC criterion can be expressed using σ_1 and σ_3

$$\sigma_{1\mathrm{MC}} = p + q\sigma_3 \tag{8}$$

where $\sigma_{1\mathrm{MC}}$ is the major principle stress of the equivalent MC criterion, and

$$p = \frac{2c\cos\varphi}{1-\sin\varphi} \tag{9}$$

$$q = \frac{1+\sin\varphi}{1-\sin\varphi} \tag{10}$$

where φ is internal friction angle, and c is cohesion.

In the sense of least squares, choose p and q to minimize the integral

$$Q = \int_{\sigma_{3a}}^{\sigma_{3b}} \left(\sigma_{1\mathrm{MC}} - \sigma_{1\mathrm{HB}}\right)^2 d\sigma_3 \tag{11}$$

A minimum of Q gives

$$p=\frac{4\left(\sigma_{3b}^{2}+\sigma_{3b}\sigma_{3a}+\sigma_{3a}^{2}\right)S_{1}-6\left(\sigma_{3b}+\sigma_{3a}\right)S_{2}}{\left(\sigma_{3b}-\sigma_{3a}\right)^{3}} \tag{12}$$

$$q=\frac{-6\left(\sigma_{3b}+\sigma_{3a}\right)S_{1}+12S_{2}}{\left(\sigma_{3b}-\sigma_{3a}\right)^{3}} \tag{13}$$

where,

$$S_{1}=\frac{1}{2}\left(\sigma_{3b}^{2}-\sigma_{3a}^{2}\right)+\frac{\sigma_{ci}^{2}}{(1+a)m_{b}}\left[\left(\frac{m_{b}\sigma_{3b}}{\sigma_{ci}}+s\right)^{1+a}-\left(\frac{m_{b}\sigma_{3a}}{\sigma_{ci}}+s\right)^{1+a}\right] \tag{14}$$

$$S_{2}=\frac{1}{3}\left(\sigma_{3b}^{3}-\sigma_{3a}^{3}\right)+\frac{\sigma_{ci}^{3}}{(2+a)(1+a)m_{b}^{2}}\left\{\begin{array}{l}\left(\dfrac{m_{b}\sigma_{3b}}{\sigma_{ci}}+s\right)^{1+a}\left[(1+a)\dfrac{m_{b}\sigma_{3b}}{\sigma_{ci}}-s\right]\\-\left(\dfrac{m_{b}\sigma_{3a}}{\sigma_{ci}}+s\right)^{1+a}\left[(1+a)\dfrac{m_{b}\sigma_{3a}}{\sigma_{ci}}-s\right]\end{array}\right\} \tag{15}$$

Using Eqs. (12) and (13), φ and c can be expressed as

$$\varphi=\arcsin\left(\frac{q-1}{q+1}\right) \tag{16}$$

$$c=\frac{p}{2\sqrt{q}} \tag{17}$$

Noted that, substituting the lower and upper limits $\sigma_{3a} = -s\sigma_{ci}/m_b$ and $\sigma_{3b} = \sigma_{3max}$ into Eqs. (12) and (13), p and q can be obtained. After p and q obtained, using Eqs. (16) and (17), the expressions of φ and c exactly identical to Eqs. (5) and (6), can be obtained.

Although Hoek et al. (2002) declared that the fitting process involves balancing the areas above and below the MC envelope, the expressions of φ and c can also be obtained using least squares approximation. It should be pointed out that $-s\sigma_{ci}/m_b$ is biaxial tensile strength σ_{t2} because substituting $\sigma_3 = -s\sigma_{ci}/m_b$ into Eq. (1) gives $\sigma_1 = -s\sigma_{ci}/m_b$.

4 Validation of the proposed solution

4.1 Example 1

The first example is adopted from Hoek et al. (2002). This is a typical example in which σ_{ci} = 50000 kPa, GSI = 45, and m_{i} = 10. For an undisturbed in-situ rock mass (D = 0) surrounding a tunnel at a depth of 100 m, $\sigma_{3\max}$ was calculated by the formula suggested by Hoek et al. (2002) for tunnels, assuming γ = 27 kN/m^3, while the lower limit of σ_3 was assumed to be $\sigma_{\mathrm{t2}} = -s\sigma_{\mathrm{ci}}/m_{\mathrm{b}}$. For the rock mass with the same parameters but in highly disturbed slope (D = 1) with 100 m height, $\sigma_{3\max}$ was calculated by the formula suggested by Hoek et al. (2002) for slopes, while the lower limit of σ_3 was also assumed equal to σ_{t2}. **Table 1**, an extract from a basic Microsoft Excel spreadsheet, illustrates that the calculated EMC parameters using the present solution agreed very well with those reported by Hoek et al. (2002). This verified the reliability and performance of the proposed solution.

4.2 Example 2

The proposed least squares solution can also be used to approximately calculate IMC parameters using a small interval of σ_3 centered at the specified σ_{30}. If σ_{n} was specified, a process of Kumar et al. (2020) should be used to calculate σ_3 corresponding to a given σ_{n}.

The second example is chosen from the works of Hoek et al. (2002). The associated parameters are as follows: σ_{ci} = 30000 kPa, σ_n = 800 kPa, GSI = 15, D = 0.7, and m_i = 16. At a given σ_n of 800 kPa, the specified σ_{30} of 480.5339 kPa was obtained using Newton-Raphson method. Thus, the interval of σ_3 was assigned to [$0.999\sigma_{30}$, $1.001\sigma_{30}$]. **Table 2** shows the IMC parameters at the specified σ_n of 800 kPa, and the results obtained from this study had a good consistence with those reported by others.

More examples published in the literature (e.g. Hoek and Brown 1997; Priest 2005; Shen et al. 2012b) were also employed for comparison, which is not presented here for space limit. The comparison demonstrates that there was a very close agreement in the values of MC parameters with the published results. This implies that the proposed solution had the capacity to accurately determine EMC parameters for different rock types over a wide range of stress levels, as well as IMC parameters at specified stress level using a small interval of σ_3.

5. Discussions

5.1 EMC parameters over the interval from uniaxial tensile strength to maximum minor principal stress

As mentioned in Section 3, the method proposed by Hoek et al. (2002) is valid only for the interval [σ_{t2}, σ_{3max}]. For practical slope stability problems, uniaxial tensile strength σ_{t1} or tension cut-off $\sigma_{cut\text{-}off}$ is a more realistic lower limit of σ_3 than σ_{t2}, although Hoek (1983) declared that σ_{t2}

is equal to σ_{t1} for brittle materials. Actually, the two tensile strength is not necessarily equal to each other (Michalowski and Park 2020); this is dependent on the curvature of initial segment of HB envelope.

Unfortunately, σ_{t1} cannot be represented by a convenient close-form expression in Eq. (1); it can be obtained by solving the HB criterion under the condition $\sigma_1 = 0$ using the Newton-Raphson method. The calculation shows that a good initial guess for σ_{t1}/σ_{ci} is $0.999\sigma_{t2}/\sigma_{ci}$, and the Newton-Raphson method can converge in 4-5 iterations with correct digits larger than 8.

Example 1 was used to investigate the difference in the values between σ_{t2} and σ_{t1} respected to HB constants. **Fig. 2** illustrates that the difference in estimated values between σ_{t1} and σ_{t2} was remarkable at a small m_i. For extremely small values of m_i, σ_{t2} was 10-20% larger than σ_{t1}. However, the difference between the two became insignificantly at a large m_i. This coincided with the conclusion drawn by Sari (2010). The EMC parameters over the intervals $[\sigma_{t2}, \sigma_{3max}]$ and $[\sigma_{t1}, \sigma_{3max}]$ were also determined for Example 1. Calculations demonstrate that the discrepancy in c and φ over the intervals $[\sigma_{t2}, \sigma_{3max}]$ and $[\sigma_{t1}, \sigma_{3max}]$ was less than 2%, even the maximum difference in values of σ_{t1} and σ_{t2} was up to 16.18% when GSI = 10, $m_i = 3$, and $D = 1$. The slight difference in EMC parameters over the two intervals was attributed to the small values of σ_{t1} and σ_{t2} when GSI and m_i was small; with the increasing GSI and m_i, the values of σ_{t1} and σ_{t2}

increased but the difference in the two values reduced and was negligible in a practical sense.

5.2 EMC parameters over the interval from tension cut-off to maximum minor principal stress

Triaxial extension test results of Ramsey and Chester (2004) were reproduced in **Fig. 3**, combined with the HB envelope. The HB envelope projects back in tensile regime to give an intercept of $\sigma_3 = \sigma_{t1} = -17.2$ MPa for $\sigma_1 = 0$; the calculated $\sigma_{t2} = -17.5$ MPa; this does not correspond to the tensile failure data which gives an average tensile strength $\sigma_3 = -7.75$ MPa. In other words, the HB criterion has no provision for predicting the tensile strength which was highlighted by the 'tension cut-off' (broken line in **Fig. 3**) (Hoek and Martin 2014). Hoek and Brown (2019) recommended that the MC parameters, derived from the HB criterion, should not be used without a tension cut-off. For practical slope stability problems, σ_{t1} or $\sigma_{\text{cut-off}}$ is a more realistic lower limit of σ_3 than σ_{t2}. For tunnel problems, zero should be a better estimate for the lower limit of σ_3.

The EMC parameters over different intervals of σ_3 were determined for the rock mass tested by Ramsey and Chester (2004), for which the associated parameters by back analysis are as follows: $\sigma_{ci} = 129300$ kPa, $m_b = 7.37$, $s = 1$, and $a = 0.5$, respectively. **Table 3** lists the EMC parameters over different intervals represented with tensile strength and slope height, to which the corresponding value of $\sigma_{3\max}$ was calculated by using the empirical formula given by Hoek et al. (2002). It is evident that the EMC parameters for the interval of σ_3 from $\sigma_{\text{cut-off}}$ to $\sigma_{3\max}$, as well as those over the interval $[0, \sigma_{3\max}]$, were markedly different from those over the interval $[\sigma_{t2}, \sigma_{3\max}]$ and $[\sigma_{t1}, \sigma_{3\max}]$. In this case, φ over the intervals $[\sigma_{\text{cut-off}}, \sigma_{3\max}]$ and $[0, \sigma_{3\max}]$ was approximately 12% and 16.5% smaller than that over the interval $[\sigma_{t2}, \sigma_{3\max}]$, respectively; c over the intervals $[\sigma_{\text{cut-off}}, \sigma_{3\max}]$ and $[0, \sigma_{3\max}]$ was approximately 10.3% and 15.7% larger than that over the interval $[\sigma_{t2}, \sigma_{3\max}]$, respectively. Thus, the practical interval of σ_3 should be carefully determined when calculating EMC parameters.

6 Conclusions

The study provided a new analytical formulation of equivalent MC shear strength parameters over an arbitrary interval of σ_3 for the HB criterion based on least squares method. Comparison with published results demonstrates that the proposed solution had the capacity to accurately determine the EMC parameters over a broad range of values of GSI, D, m_i, and σ_{ci}. Some conclusions can be drawn as follows:

(1) The proposed solution was valid to determine EMC parameters over an arbitrary interval of σ_3. The solution for the EMC parameters provided by Hoek et al. (2002) is a special case of the proposed solution in case that the lower limit of σ_3 equals to the biaxial tensile strength σ_{t2}.

(2) The present solution can also be used to approximately calculate IMC parameters at a specified σ_n using a very small interval of σ_3. The comparison demonstrates that there was a close agreement in the values of IMC parameters published in the literature.

(3) The calculated EMC parameters heavily depended on the specified interval of σ_3. The discrepancy in φ and c over the intervals $[\sigma_{t2}, \sigma_{3\max}]$ and $[\sigma_{t1}, \sigma_{3\max}]$ was negligible in a practical sense. A calculation case demonstrates that the equivalent φ over the intervals $[\sigma_{\text{cut-off}}, \sigma_{3\max}]$ and $[0, \sigma_{3\max}]$ was approximately 12% and 16.5% smaller than that over the interval $[\sigma_{t2}, \sigma_{3\max}]$, respectively; the equivalent c over the intervals $[\sigma_{\text{cut-off}}, \sigma_{3\max}]$ and $[0, \sigma_{3\max}]$ was approximately 10.3% and 15.7% larger than that over the interval $[\sigma_{t2}, \sigma_{3\max}]$, respectively.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this note.

List of Notations

a	Hoek-Brown material constant
c	Cohesion of equivalent Mohr-Coulomb criterion (kPa)
D	Disturbance factor
GSI	Geological Strength Index of rock mass
H_s	Height of slope (m)
H_t	Depth of tunnel below surface (m)
m_b	Hoek-Brown material constant of rock mass
m_i	Hoek-Brown material constant of intact rock
p	Auxiliary variable
q	Auxiliary variable
Q	Integral of squared residuals over an interval of minor principal stress
s	Hoek-Brown material constant
S_1	Auxiliary variable
S_2	Auxiliary variable
φ	Internal friction angle of equivalent Mohr-Coulomb criterion (°)
σ_1	Major principal stress (kPa)
σ_1HB	Major principal stress of Hoek-Brow criterion (kPa)
σ_1MC	Major principal stress of equivalent Mohr-Coulomb criterion (kPa)
σ_3	Minor principal stress (kPa)
σ_{30}	Specified minor principal stress (kPa)
σ_3a	Lower limit of minor principal stress (kPa)

σ_{3b}	Upper limit of minor principal stress (kPa)
σ_{3max}	Maximum minor principal stress (kPa)
σ_{ci}	Uniaxial compressive strength of intact rock (kPa)
σ_{cm}	Rock mass strength (kPa)
$\sigma_{cut\text{-}off}$	Tension cut-off (kPa)
σ_n	Normal stress (kPa)
σ_t	Tensile strength (kPa)
σ_{t1}	Uniaxial tensile strength (kPa)
σ_{t2}	Biaxial tensile strength (kPa)
τ	Shear strength (kPa)
γ	Unit weight of rock mass (kN/m^3)

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(Single column, Color online only)

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The tables in this work were created by MSOffice.

Figures

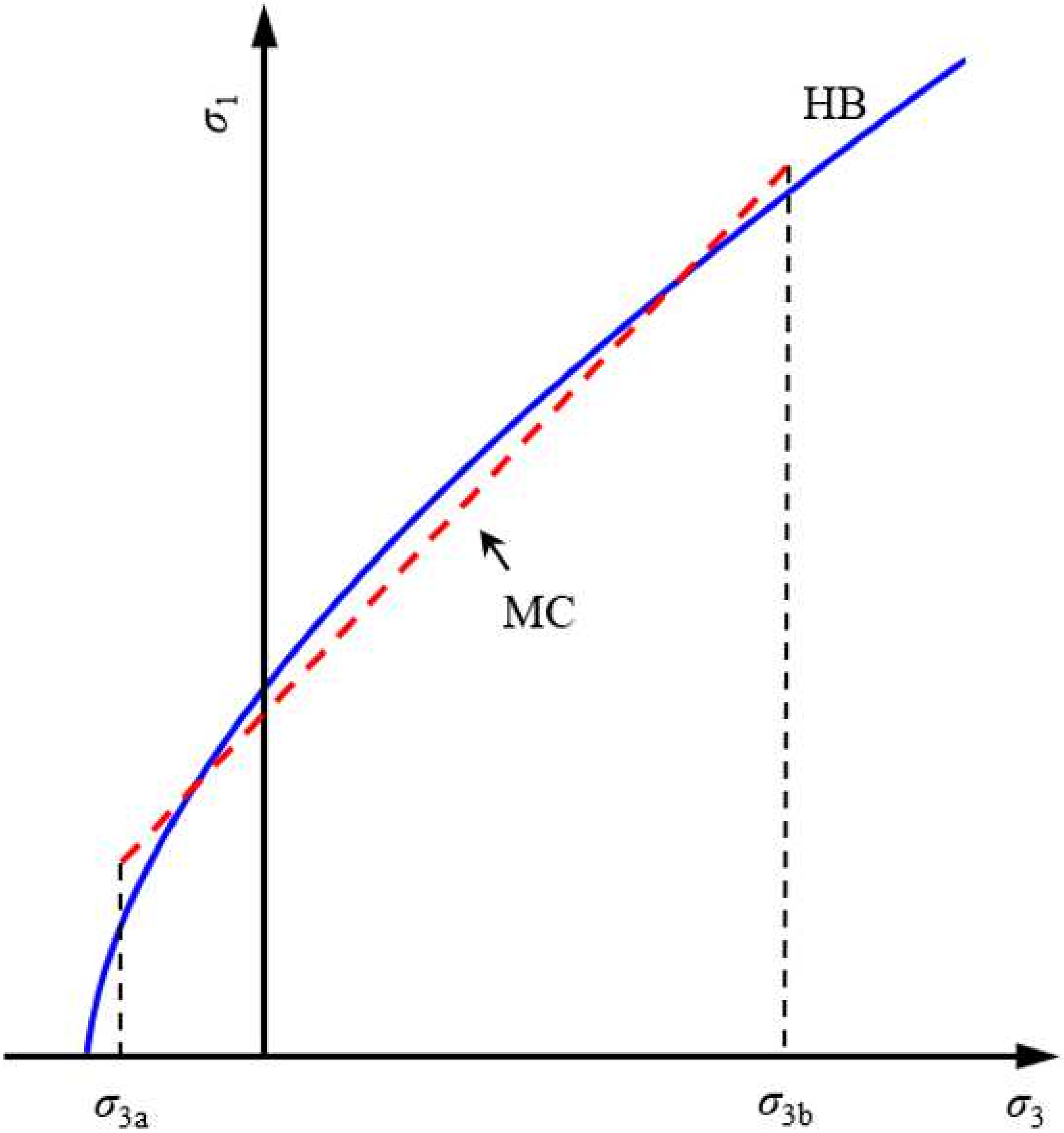

Figure 1

Equivalent MC criterion for HB criterion (Single column, Color online only)

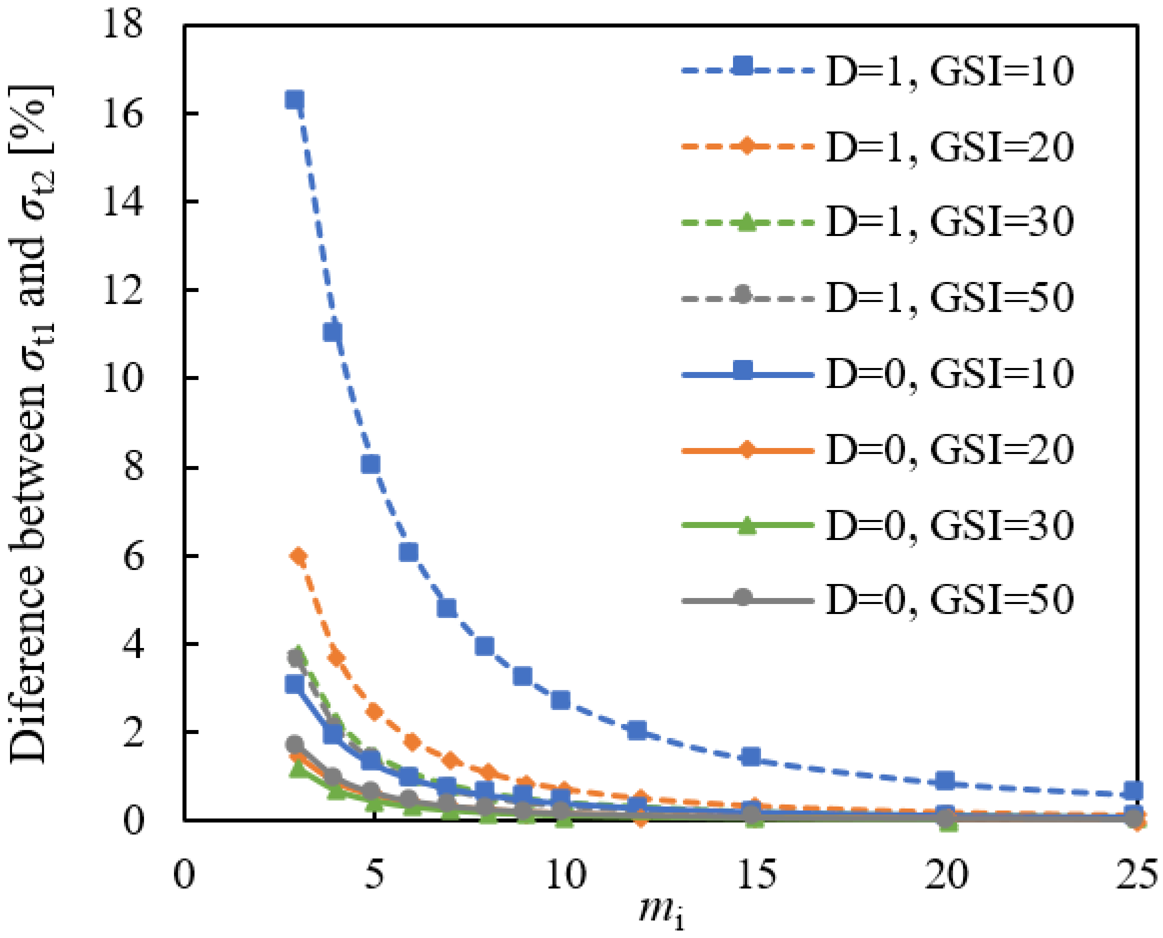

Figure 2

Difference in the values between the biaxial and uniaxial tensile strength (Single column, Color online only)

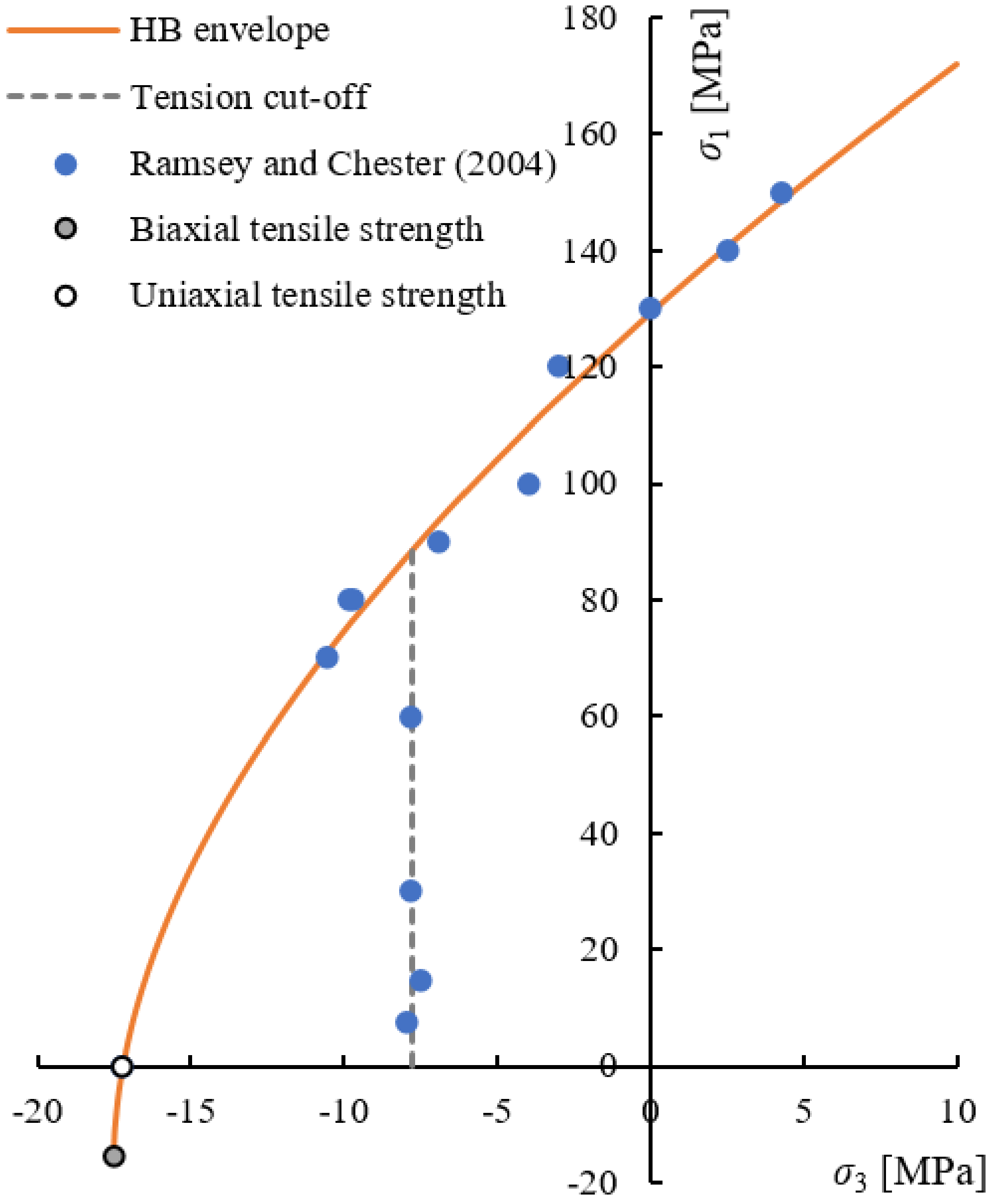

Figure 3

Combined plot of HB criterion with tension cut-off (Single column, Color online only)