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MODIFIED LOCAL STABILITY FACTOR*

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Abstract In the past，stability evaluation of engineering rockmass is often based on the distribution of stress and deformation in engineering rockmass. Some scholars have put forward the concept of local stability factor of rockmass and its calculating method. But its condition is too harsh. The concept of is put forward and its formula is deduced based on the rockmass mechanics principle and strength criteria. The modified local stability factor has been used to evaluate the stability of surrounding rockmass of tunnel.

Key words rock mechanics，stability of rockmass，local stability factor of engineering rockmass

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1 INTRODUCTION

With a great increase in the power of digital computers，the numerical analysis methods for the engineering purpose have been developed in the last decade. Especially，the stress analysis is one of the most popularly used numerical methods. The calculated results of the stress analysis are usually illustrated by stress contour. However，only stress is not enough to estimate the degree of safety or stability for the material strength depending on confining pressure. In such cases，local stability factor such as proposed by Ono (1962) or stress severity(inverse of local stability factor) such as proposed by Fairhurst (1964) is popularly used to illustrate the state of stress at any point in the structure[1，2]. Each definition of the stability factor for every failure criterion was proposed according to whether three principal stresses increase proportionally with each other，and reach on the plane of the failure criterion. However，the principal stresses at any point in the structure are hardly in proportion. In this paper，a modified local stability factor is put forward，which is also considered to be applicable to most of the failure criteria proposed so far. For validation，the local stability factor calculated by the modified definition is compared with calculating results by the former definitions.

2 FORMER AND MODIFIED DEFINITIONS OF LOCAL STABILITY FACTOR

2.1 Former definition of local stability factor

Local stability factor (S_f) at a point A (σ_1，σ_2，σ_3) in Fig.1 is defined as

$$S_f = D / d \tag{1}$$

where d is the distance from the origin to point A(σ_1，σ_2，σ_3) in the stress coordinate system. Suppose that three principal stresses increase proportionally with each other，and reache on the plane of the failure criterion at point B(σ_1'，σ_2'，σ_3')，then D is the distance from the origin to the point B. A failure criterion can be expressed as

$$f(\sigma_1'，\sigma_2'，\sigma_3') = 0 \tag{2}$$

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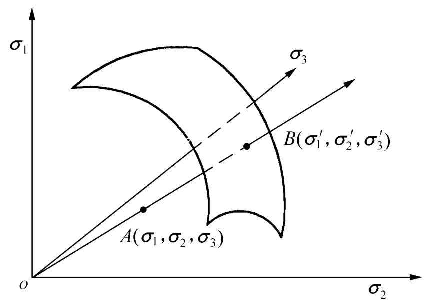


Fig.1 Original definition of stability factor

It is apparent from the definition of the former stability factor that

$$S_{\mathrm{f}} = \sigma_1' / \sigma_1 = \sigma_2' / \sigma_2 = \sigma_3' / \sigma_3 \tag{3}$$

Substituting Eq.(3) to Eq.(2)，we get

$$F(S_{\mathrm{f}}\sigma_1 , S_{\mathrm{f}}\sigma_2 , S_{\mathrm{f}}\sigma_3) = 0 \tag{4}$$

If the values of principal stresses are given，the value of S_{f} can be readily calculated by Eq.(4).

According to the definition of stability factor，the formula deduced for calculating stability factor are listed as follows(σ_{c} and σ_{t} are compressive and tensile strengths in follow equations)：

(1) Coulomb′s criterion

The failure criterion：$\sigma_1 / \sigma_{\mathrm{c}} - \sigma_1 / \sigma_{\mathrm{t}} = 1.0$ (5)

When $\sigma_1 / \sigma_{\mathrm{c}} - \sigma_1 / \sigma_{\mathrm{t}} = 1.0 > 0$,

$$S_{\mathrm{f}} = \sigma_{\mathrm{c}}\sigma_{\mathrm{t}} / (\sigma_1\sigma_{\mathrm{t}} - \sigma_3\sigma_{\mathrm{c}}) \tag{6}$$

When $\sigma_1 / \sigma_{\mathrm{c}} - \sigma_1 / \sigma_{\mathrm{t}} \leqslant 0$, S_{f} has no definition.

(2) Mohr′s criterion

The failure criterion：$\tau^2 = \sigma_{\mathrm{t}}(\sigma - \sigma_{\mathrm{t}})$ (7)

When $\sigma \geqslant -\sigma_{\mathrm{t}}$,

$$S_{\mathrm{f}} = \frac{m\sigma\sigma_{\mathrm{t}}}{2\tau^2} + \frac{m\sigma_{\mathrm{t}}}{2\tau}\sqrt{\frac{\sigma^2}{\tau^2} + \frac{4}{m}} \tag{8}$$

When $\sigma < 0$, S_{f} has on definition. m is a parameter.

(3) Bieniawski′s criterion[3]

The failure criterion：

$$\sigma_1 = \sigma_{\mathrm{c}} + \beta\sigma_{\mathrm{c}}(\sigma_3 / \sigma_{\mathrm{c}})^{\alpha} \tag{9}$$

When $\sigma_3 > 0$, S_{f} is the solution of Eq.(10).

$$\sigma_{\mathrm{c}}^{\alpha} - \sigma_1\sigma_{\mathrm{c}}^{\alpha-1}S_{\mathrm{f}} + \beta\sigma_3^{\alpha}S_{\mathrm{f}}^{\alpha} = 0 \tag{10}$$

When $\sigma_3 \leqslant 0$, S_{f} has on definition. α , β are parameters.

(4) Hoek and Brow′s criterion[4]

The failure criterion：

$$\sigma_1 \geqslant \sigma_3 + \sigma_{\mathrm{c}}(1 + m\sigma_3 / \sigma_{\mathrm{c}})^{\frac{1}{2}} \tag{11}$$

$$S_{\mathrm{f}} = \frac{2\sigma_{\mathrm{c}}}{\sqrt{m^2\sigma_3^2 + 4(\sigma_1 - \sigma_3)^2 - m\sigma_3}} \tag{12}$$

here，$\dfrac{\sigma_{\mathrm{c}}}{\sigma_{\mathrm{t}}}\left(1 - \dfrac{\sigma_{\mathrm{t}}^2}{\sigma_{\mathrm{c}}^2}\right) \geqslant 0$

(5) Johnston′s criterion[5]

The failure criterion：$\sigma_1 \geqslant \sigma_{\mathrm{c}}\left[\left(\dfrac{M}{\beta}\right)\left(\dfrac{\sigma_3}{\sigma_{\mathrm{c}}}\right) + 1\right]^{\beta}$ (13)

When $\sigma_1 > 0$, S_{f} is the solution of Eq.(14).

$$S_{\mathrm{f}} = \frac{\sigma_{\mathrm{c}}}{\sigma_1}\left[\left(\frac{M}{\beta}\right)\left(\frac{\sigma_3}{\sigma_{\mathrm{c}}}S_{\mathrm{f}}\right) + 1\right]^{\beta} \tag{14}$$

When $\sigma_1 \leqslant 0$，S_{f} has no definition，M is a parameter.

(6) Misses′s criterion

The failure criterion：

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \geqslant 2\sigma_{\mathrm{c}} \tag{15}$$

$$S_{\mathrm{f}} = \frac{2\sigma_{\mathrm{c}}}{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}} \tag{16}$$

(7) Druger-Plager′s criterion[6]

The failure criterion：

$$\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \geqslant \sqrt{6}[\alpha(\sigma_1 + \sigma_2 + \sigma_3) + k] \tag{17}$$

When

$$\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \geqslant \left(\frac{\sigma_{\mathrm{c}} - \sigma_{\mathrm{t}}}{\sigma_{\mathrm{c}} + \sigma_{\mathrm{t}}}\right)(\sigma_1 + \sigma_2 + \sigma_3) \tag{18}$$

$$S_{\mathrm{f}} = \frac{\sqrt{2}(\sigma_{\mathrm{c}} - \sigma_{\mathrm{t}})}{4\sigma_{\mathrm{c}}\sigma_{\mathrm{t}}} \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} - \frac{\sigma_{\mathrm{c}} - \sigma_{\mathrm{t}}}{2\sigma_{\mathrm{c}}\sigma_{\mathrm{t}}}(\sigma_1 + \sigma_2 + \sigma_3) \tag{19}$$

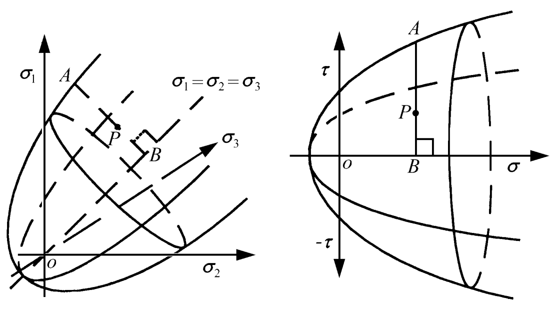
When

$$\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} < \left(\frac{\sigma_{\mathrm{c}} - \sigma_{\mathrm{t}}}{\sigma_{\mathrm{c}} + \sigma_{\mathrm{t}}}\right)(\sigma_1 + \sigma_2 + \sigma_3) \tag{20}$$

S_{f} has no definition.

2.2 A modified local stability factor

We know that material fails in the two types，e.g. tensile and shear failure respectively. According to their physical significance and mechanical concept， the farther the distance of point P to point B(Fig.2) is，the larger the probability of failure is，so the stability factor can be defined as



(a) Principal stress-coordinate (b) Normal shear stress-coordinate

Fig. 2 Definition of modified stability factor

$$S_{\rm f}=\frac{\overline{ab}}{\overline{pb}} \tag{21}$$

where $\overline{ab}$ and $\overline{pb}$ are length of line segments AB and PB respectively[7~14]. According to the definition of stability factor，the formula deduced for calculating stability factor are listed as follows：

(1) Coulomb′s criterion

When $\sigma_3>-\sigma_{\rm t}$，

$$S_{\rm f}=\frac{(\sigma_1+\sigma_3)(\sigma_{\rm c}-\sigma_{\rm t})+2\sigma_{\rm c}\sigma_{\rm t}}{(\sigma_1-\sigma_3)(\sigma_{\rm c}+\sigma_{\rm t})} \tag{22}$$

When $\sigma_3<-\sigma_{\rm t}$，$S_{\rm f}=0.0$。

(2) Mohr′s criterion

When

$$S_{\rm f}=\frac{2\sqrt{[\sigma_A-(\sigma_1+\sigma_3)/2]^2+m\sigma_{\rm t}(\sigma_A-\sigma_{\rm t})}}{\sigma_1-\sigma_3} \tag{23}$$

When $\sigma_3\leqslant-\sigma_{\rm t}$，$S_{\rm f}=0.0$，$\sigma_A$ is the real solution of the Eq.(24).

$$\sigma_A^3-(\sigma_1+\sigma_2+\sigma_{\rm t})\sigma_A^2+\frac{1}{4}(\sigma_1+\sigma_3)(\sigma_1+\sigma_3+4\sigma_{\rm t})\sigma_A-\frac{1}{4}(\sigma_1+\sigma_3)^2-\frac{1}{16}m^2\sigma_{\rm t}(\sigma_1-\sigma_3)^2+\frac{1}{16}m^4\sigma_{\rm t}^3=0 \tag{24}$$

(3) Bieniawski′s criterion

When $\sigma_3>-\sigma_{\rm t}$，

$$S_{\rm f}=\sqrt{\frac{(\sigma_1+\sigma_3-2\sigma_{\rm c}-2\beta\sigma_{\rm c}^{1-\alpha}\sigma_{3A})^2}{4(\sigma_1-\sigma_3)^2}} \tag{25}$$

When $\sigma_3\leqslant-\sigma_{\rm t}$，$S_{\rm f}=0$. Here σ_{3A} is solution of Eq.(26)

$$\sigma_{3A}=\sigma_1-\sigma_3-\sigma_{\rm c}-\beta\sigma_{\rm c}^{1-\alpha}\sigma_{3A}^{\alpha} \tag{26}$$

(4) Hoek and Brown′s criterion

$$S_{\rm f}=\frac{\left[\dfrac{m\sigma_{\rm c}}{4}-\sqrt{\left(\sigma_1+\sigma_3+\dfrac{m\sigma_{\rm c}}{4}\right)^2-(\sigma_1-\sigma_3)^2+\sigma_{\rm c}^2}\right]}{\sigma_1-\sigma_3} \tag{27}$$

(5) Johnston′s criterion

$$S_{\rm f}=\frac{\sigma_1+\sigma_3-2\sigma_{\rm c}\left[\left(\dfrac{m}{\beta\sigma_{\rm c}}\right)(\sigma_1+\sigma_3-\sigma_{1A})+1\right]^{\beta}}{\sigma_1-\sigma_3} \tag{28}$$

where σ_{1A} is a solution of Eq.(29)：

$$\sigma_{1A}=\sigma_{\rm c}\left[\left(\frac{m}{\beta\sigma_{\rm c}}\right)(\sigma_1+\sigma_3-\sigma_{1A})+1\right]^{\beta} \tag{29}$$

(6) Mises′s criterion

$$S_{\rm f}=\frac{\sqrt{6}\sigma_{\rm c}}{\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}} \tag{30}$$

(7) Druger-Plager′s criterion

$$S_{\rm f}=\frac{\sqrt{6}[\alpha(\sigma_1+\sigma_2+\sigma_3)+1]}{\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}} \tag{31}$$

3 THE COMPARISON OF $S_{\rm f}$

3.1 The models and the results

To examine the calculating results with local stability factor definition，the models of the tunnel is established(Fig.3). First，the principal stresses are calculated by FEM and then local stability factor of each element is calculated according to the stresses in the former definition and modified definition of stability factor respectively. The change of $S_{\rm f}$ with horizontal distance from the driving face of the tunnel is shown in Figure 4.

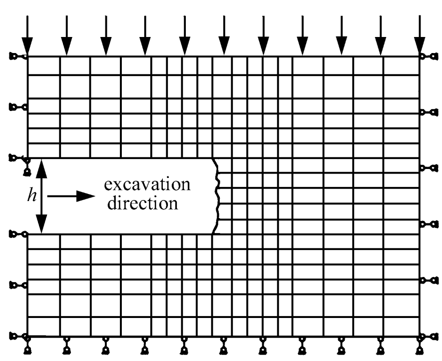
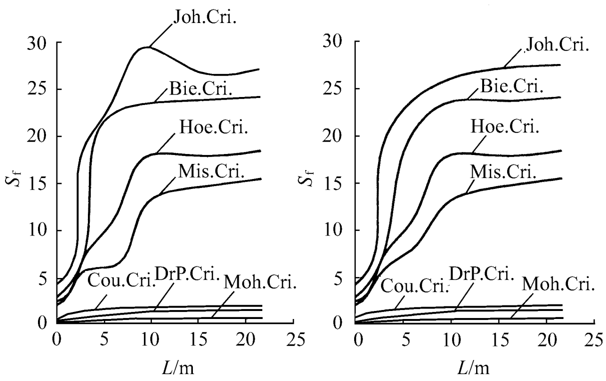


Fig. 3 FEM model of tunnel



(a) Stability factor surrounding tunnel according modified definition　(b) Stability factor surrounding tunnel according former definition

Fig.4　Variation of S_f with horizontal distance to the tunnel face

3.2 Discussion

The theory of the stability factor is a good thought and method for evaluating comprehensively how stable of the engineering rockmass is，which contains not only the stresses (external condition of rockmass system) in the rock，but also strength properties of the rock (internal condition). Generally speaking，a stability factor is usually defined for each failure criterion. The suitability and validity are different with the failure criterion. For above reason，we should discuss the distribution of the stability factor according to the seven failure criteria.

(1) The stability factor based on modified definition

In Fig. 4(b)，the stability factor first increases and then decreases and tends to a constant at last with the distance from the analytical point to working face of the tunnel. The results are corresponding with actual mechanical phenomena investigated during tunnel excavation，except Coulomb′s，Mohr′s and Druger-Plager′s criterion，which always increase with the distance.

(2) The stability factor based on the former definition

For most points，the varia-tion of S_f with the distance from analysis point to working face of tunnel，according to former defini-tion，are similar to the variation of S_f calculated based on the modified definition，in Fig. 4(a).

(3) The comparison of S_f based on former and modified definition

In the practice of rockmass engineering，three principal stresses in rockmass do not variate proportionally with each other. Additionally，according to physical concept and mechanical principle，in some very safe area in principal stress or shear-normal stress coordinates，stability factor has no definition by former concept，such as Coulomb and Druger Plager′s criteria，or is negative，such as Bieniawski and Johnston′s criteria. It means that the conditions requested by former definition are very harsh. The modified definition of stability factor does not need above condition，which is determined by actual stress condition acting on the rockmass，and the stability factor has definition and is positive. From Fig.4 and discussion，it is well known that the stability factors calculated in modified definition are less than that calculated in former definition according to different criteria.

4 CONCLUSION

Several conclusions could be derived from above discussion. Applicability of the local stability factor has relation with stress condition，which is tensile or compressive in rockmass. Among above seven criteria，Coulomb，Hoek and Brown，Druger-Plager′s criteria are better than the other four criteria for evaluating the stability of rockmass surrounding tunnel. The modified definition of stability factor is more suitable and applicable than former definition. Because former definition of local stability needs more conditions than modified defini-tion of local stability，the latter is more convenient than the former in practice application.

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裂隙非饱和渗流试验研究及有地表入渗的裂隙岩体渗流数值分析

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博士学位论文摘要　就单裂隙非饱和水力参数的试验测定和数值模拟确定、单裂隙非饱和渗流的机理、有地表入渗的裂隙岩体饱和非饱和渗流数值分析以及地表入渗对岩坡稳定性的影响等方面展开了较为深入的研究，并将上述研究成果应用于实际大型工程问题的分析中。主要内容如下：

(1) 借鉴前人的研究成果，基于动力法原理(即逐次建立水相和气相之间的稳定流动状态)，首次研制出一套可同时测定单裂隙毛细压力-饱和度以及非饱和渗透系数-毛细压力关系的实验装置，并提出一种用该实验装置来测定单裂隙非饱和水力参数的物模试验法，使得通过试验来测定单裂隙非饱和水力参数成为可能。

(2) 运用分形几何和蒙特卡洛模拟等理论，提出一种更合理的确定单裂隙非饱和水力参数的数值试验法，并开发相应的模拟程序。由于该法在生成裂隙充水域时考虑了水和气的“圈闭”效应，故能模拟出裂隙排水与吸水过程间客观存在的滞后现象，这是以往数值试验法所不能做到的。

(3) 把裂隙岩体等效为连续介质来处理，建立有地表入渗的裂隙岩体饱和非饱和渗流的数学模型。以 Galerkin 有限元法为模拟手段，研制了相应的算法，并编制了考虑地表入渗的三维饱和非饱和渗流有限元计算程序 SUSS3D。算例分析表明，上述模型和计算程序是合理可行的。

(4) 引入非饱和土的抗剪强度理论，运用刚体极限平衡法，研制出了地表入渗影响下的岩坡稳定性验算程序 ZSLP。该程序考虑了非饱和带基质吸力对岩体抗剪强度的贡献以及暂态附加水荷载的不利作用，使计算结果更贴近实际。

(5) 将上述研究成果应用于小湾电站水垫塘区岸坡降雨入渗分析，溪洛渡电站水垫塘区岸坡雾化雨入渗分析以及雾化雨入渗对溪洛渡电站水垫塘区岸坡稳定性的影响等实际工程问题的研究。结果表明：地表入渗确会给边坡稳定带来不利的影响，并且本文的模型和计算程序均是合理可行的。

关键词　裂隙岩体，非饱和渗流，试验研究，地表入渗，非饱和水力参数，数值分析，岩坡稳定

TESTING STUDY ON UNSATURATED SEEPAGE IN FRACTURE AND NUMERICAL ANALYSIS ON SEEPAGE IN FRACTURED ROCK MASS DUE TO SURFACE INFILTRATION

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