A Comparison Between Hoek-Brown and Bieniawski Criteria for Coal and Rocks

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ABSTRACT

The applicability of Bieniawski and Hoek-Brown empirical strength criteria has been assessed for different groups of coal and various types of intact rocks by using a vast number of published triaxial test data from various places. Analysis of individual data sets revealed that the traditional forms of the criteria do not have a perfect agreement with the data. A strong negative correlation has been observed between B in Bieniawski's criterion and m in Hoek and Brown's criterion with uniaxial compressive strength of materials. Both criteria have been modified and empirical relationships have been introduced for coal as follows:

$$m = 62.903 - 34.213\ (log\ \rho_c)^{0.9772}$$

$$B = 10.152 - 4.709\ (log\ \rho_c)^{0.8889}$$

Similar relationships have been developed for different rock types as well.

A comparison between the applicability of each of the above approaches with the conventional criteria reveals a very significant advantage for new approaches and a supremacy for the Bieniawski criterion in all cases particularly in the case of coal.

The modified Bieniawski criterion fits coal as well as different types of rocks with excellent accuracy.
The modified Hoek-Brown criterion gives a good result for rocks but does not fit coal data quite well. In other words, Hoek-Brown criterion is not an suitable one for coal.

INTRODUCTION

To estimate the strength of rock and rock mass a failure criterion is required. The theoretical triaxial strength criteria based on the actual mechanism of fracture do not fit the experimental results properly and to overcome this problem, many empirical criteria have been formulated for rocks.

Laboratory strength data values are the starting points for estimating the strength of rock and rock mass. If a criterion fails to fit the laboratory strength data properly, then its applicability to real field cases would certainly be doubtful.
Out of many strength criteria developed so far, none of them has been accepted to be a global formula capable of simply describing the strength of geomechanical materials in general.

Coal is one of the most important energy resources. As it is widely mined around the world, and receiving attention on the current mining and energy scene, developing an appropriate strength criterion for use in coal seams to be of considerable value.

Amongst all available strength criteria proposed for the estimation of the strength of rocks and geomechanical materials, a very few of them have been extended to coal. One criterion proposed for coal is that suggested by Sheorey, Biswas and Choubey(1989). Using this criterion in practice requires a very long complicated procedure, as it is understood from the

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original paper. None of the two failure criteria examined in this investigation(i.e. Hoek-Brown, 1980a&b and Bieniawski,1974) have taken coal into consideration and the appropriate values for constants are not available for the same.

STRENGTH CRITERIA

The general form of a strength criterion is:

$$\rho_1 = f(\rho_2, \rho_3)$$

where ρ_1, ρ_2 and ρ_3 are the principal stresses at failure.

Because the available data indicate that the intermediate principal stress, ρ_2, has very little influence on strength than the minor principal stress, ρ_3, all of the criteria used in practice are reduced to the form:

$$\rho_1 = f(\rho_3)$$

or in its normalised form;

$$\frac{s_1}{s_c}) = f(\frac{s_3}{s_c})$$

Hoek-Brown's criterion for intact rocks

$$\frac{\sigma_1}{\sigma_c} = \frac{\sigma_3}{\sigma_c} + (1 + m\frac{\sigma_3}{\sigma_c})^{0.5} \quad (1)$$

m = a constant value for each rock type

Bieniawski's criterion for intact rocks

$$\frac{\sigma_1}{\sigma_c} = 1 + B(\frac{\sigma_3}{\sigma_c})^{\alpha} \quad (2)$$

B = a constant value for each rock type and
ρ = 0.65 or 0.75 for all rock type

DATA SELECTED FOR ANALYSIS

Coal data representing twenty six seams and collieries are from two publications (Hobbs, 1964 and Das and Sheorey, 1986). These data are homogeneous and on specimens of almost the same size. Thus, they are to a reasonable extent free from the effects of specimen size.

Intact rocks data include various types of geomechanical materials of diverse lithological and mechanical characteristics from weak over-consolidated clays of unconfined compressive strength of 24 MPa to strong hard granite and granodiorite of unconfined compressive strength of 427 MPa.

ANALYSING THE APPLICABILITY OF THE CRITERIA FOR INTACT COAL

Analysis of individual data sets revealed that none of the existing criteria shows perfect agreement with experimental values of coal strength. Although unique values of the constants in both criteria have been determined with good coefficients of determination for overall data, a wide variation has been noticed in the values of the constants when individual data sets have been analysed.

Hoek and Brown's criterion

The value for *m* has been determined to be 25.132 for the combination of all the 180 pairs of the data. The coefficient of determination has been found to be 0.9105. Plot of all data along with regression curve is shown in Fig. 1.

When the data groups are analysed individually, the out comes differ widely from what is achieved by mixing the whole data of all groups. In general, the best correlation amongst all single constant values assigned to *m* was due to *m* =10 (suggested for mudstone, siltstone, shale and slate by Hoek and Brown). Fig. 2 shows six examples of those cases for which by applying this criterion the lowest correlation with exact data has been obtained.

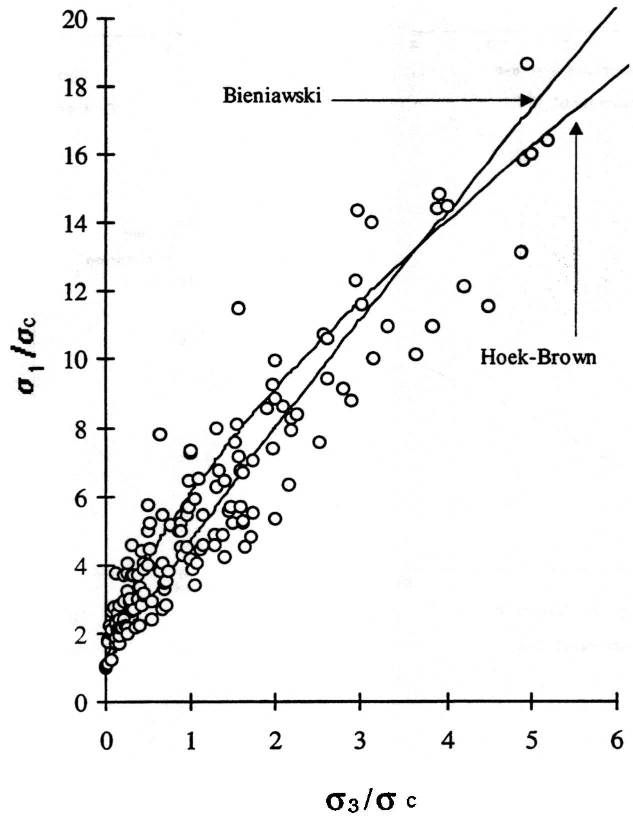

Fig. 1 - Plot of $\frac{s_1}{s_c}$ versus $\frac{s_3}{s_c}$ for all data along with regression lines according to the two criteria.

Analysis of individual data sets has given a range of values from 5.3795 to 50.190 for *m*. Analysis of these values along with ρ_c has indicated that there is a significant correlation between them (Fig. 3). The relationship between *m* and $•_c$ has been found to be as follows:

$$m = 62.903 - 34.213\ (\log \rho_c)^{0.9772} \quad (3)$$

Bieniawski's criterion

A plot of $\frac{s_1}{s_c}$ versus $\frac{s_1}{s_c}$ for all data along with the regression curve is shown in Fig. 1. The values for *B* and • have been determined to be 3.7062 and 0.9225 respectively. The coefficient of determination has been found to be 0.9551.

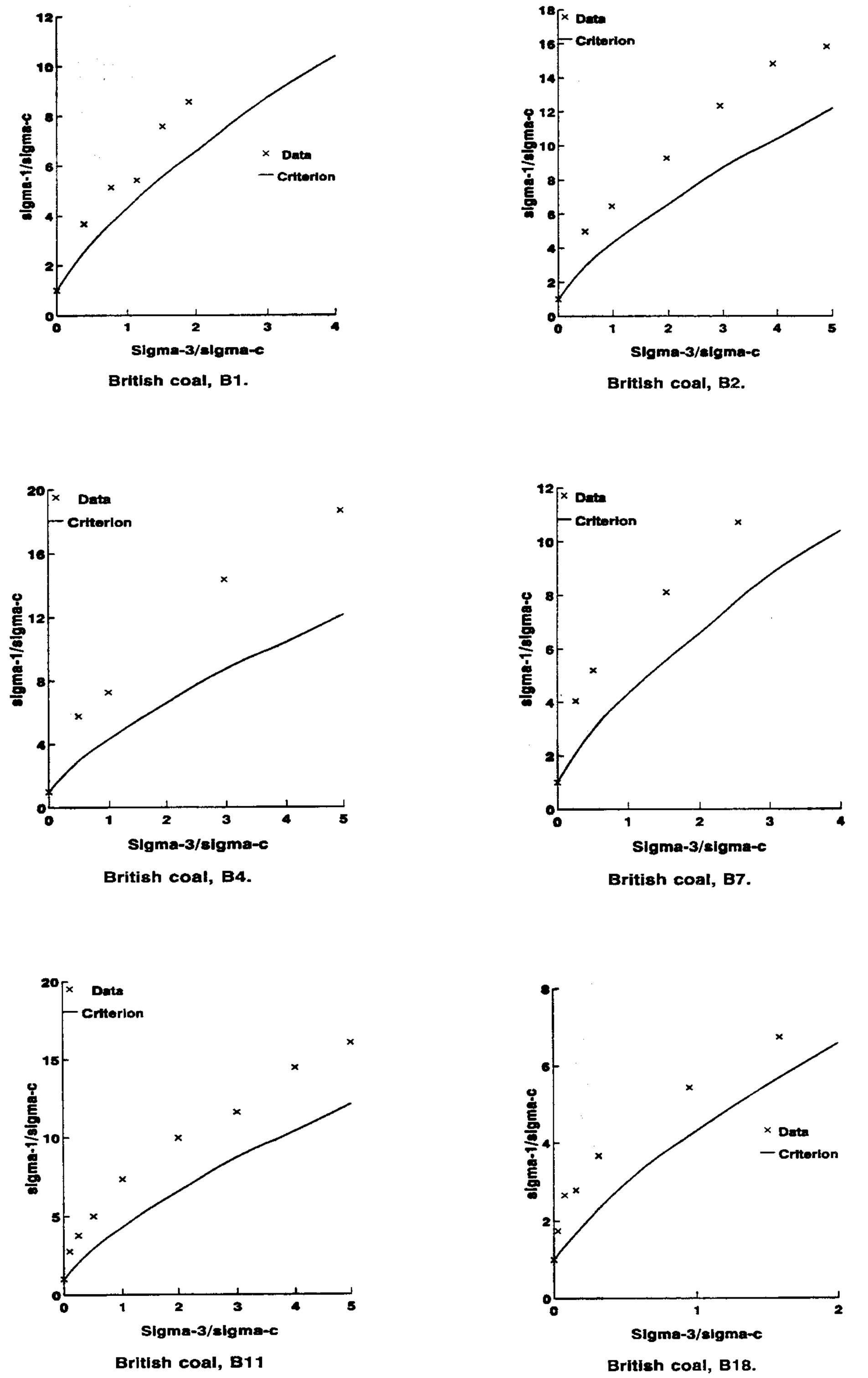

Fig. 2 - Examples of discrepancy in the traditional Hoek-Brown criterion for coal.

		m vs UCS for coal in H&B criterion
sima-c	m	m=f(sima-c)
2.21	50.19	50.83043
5.31	37.445	37.91285
6.89	33.772	34.10938
6.96	42.9	33.96203
7.03	29.58	33.81617
10.41	25.228	28.10669
13.24	25.228	24.62037
13.51	34.121	24.32804
14.3	17.715	23.5054
15.6	15.447	22.24664
15.72	22.793	22.13583
15.86	21.092	22.00762
17.8	15.691	20.33981
18.13	21.511	20.07446
21.72	27.364	17.46677
21.79	13.221	17.42036
23.58	16.511	16.28198
23.86	17.867	16.11182
27.8	8.3715	13.91007
30.27	11.142	12.6848
31.58	17.648	12.07522
35.3	7.8885	10.47376
40.3	10.553	8.570209
42.8	5.3795	7.705854
43.7	8.6629	7.40707
51.37	5.8664	5.086603

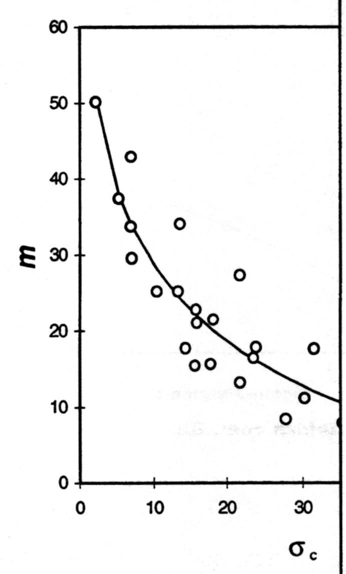

Fig. 3 - Plot of *m* versus ρ_c in Hoek and Brown's criterion for coal

The best result amongst all various constant amounts of *B* was obtained for the case in which ρ = 0.65 and B = 3.0. Fig. 4 demonstrates six examples of the cases in which this criterion has given the lowest coincidence with real data (for ρ =0.65 and B = 3.0).

Analysis of individual data sets has given a range of values for best fitting *B* from 2.22 to 6.8326 and for best fitting ρ from 0.4517 to 0.7423.

The best statistical average for ρ was found to be 0.6. Taking ρ as 0.6, the values for parameter *B* have been recalculated for all the individual data sets. From this analysis, *B* has been found to be between 2.0663 and 7.7150 and the relationship between *B* and ρ_c has been found to be as follows:

$$B = 10.152 - 4.709 \ (\log \rho_c)^{0.8889} \quad (4)$$

The coefficient of determination for this regression has been found to be 0.9164 (Fig. 5). Fig. 6 depicts the correlation between modified Bieniawski criterion with 6 groups of experimental data for which the lowset coefficient of determination was observed. Comparison of Figs. 2 and 4 with Fig. 6 reveals the supremacy of the new version of the Bieniawski criterion.

ANALYSING THE APPLICABILITY OF THE CRITERIA FOR INTACT ROCKS

The same analysis as conducted for coal was carried out for different rock types, namely, limestone, granite, granodiorite, shale, sandstone, claystone and liparite. Although the data were from various sources with differences in techniques ,size and shape of specimens, the results indicate that the parameters can not be regarded as constant values. For each particular rock type there found to be a correlation between *B* in the Bieniawski criterion and *m* in the Hoek-Brown criterion with ρ_c. ρ in the Bieniawski criterion takes different values for different types of rocks. Limestone and granite are taken as two examples.

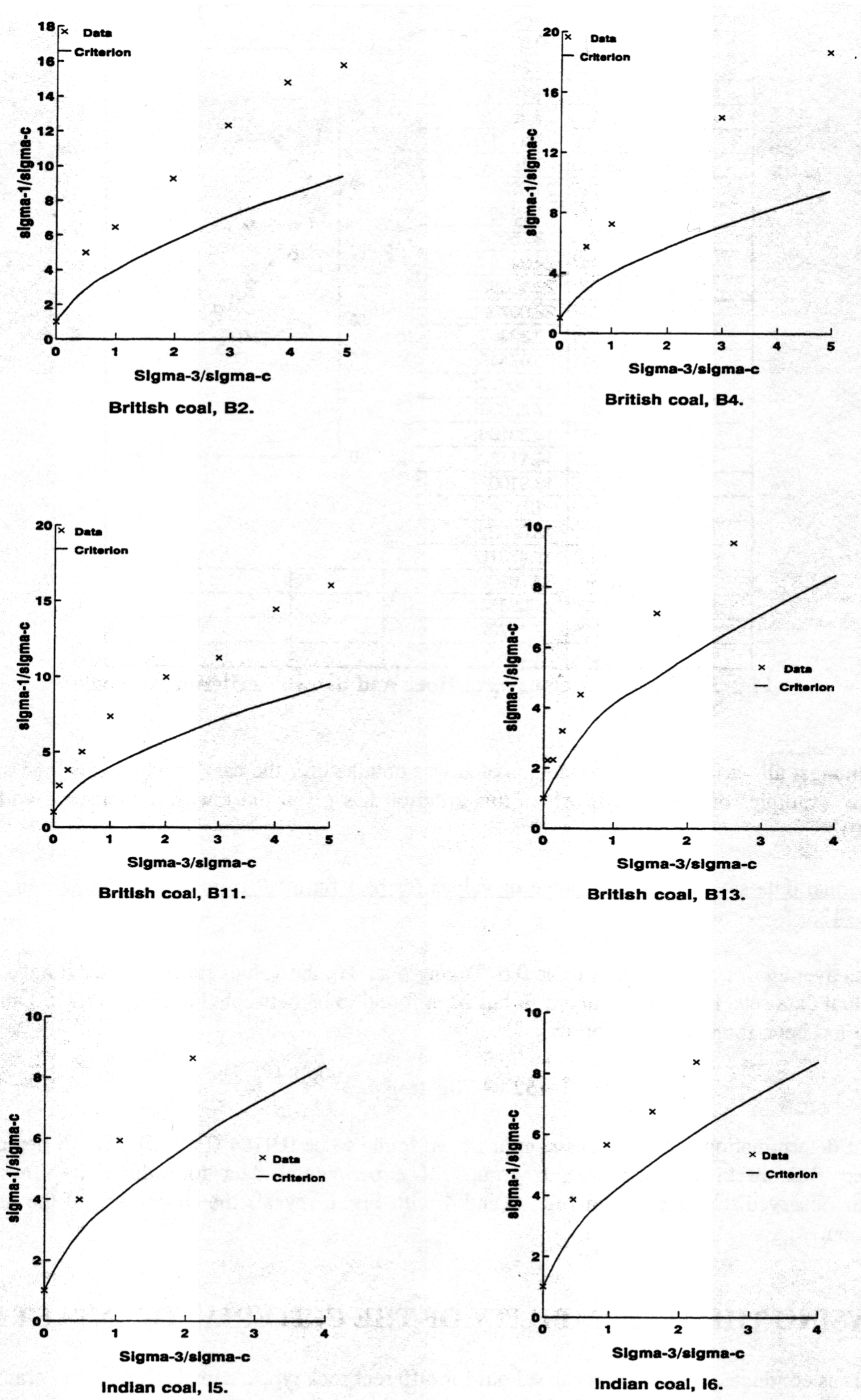

Fig. 4 - Examples of discrepancy in the traditional Bieniawski criterion for coal

The values of α and the relationships between B and m with ρ_c for these two cases are as follows:

for limestone;
α =0.76

$$B = -3.3538+10.883 \log(\rho c)^{-0.8131} \quad (5)$$

$$m = -1.6115 + 62.05 \log(\rho c)^{-2.7421} \quad (6)$$

for granite;
α =0.65

$$B = 3.4452 + 21.617 \log(\rho c)^{-2.757} \quad (7)$$

$$m = -971 + 1055.3 \log(\rho c)^{-0.06} \quad (8)$$

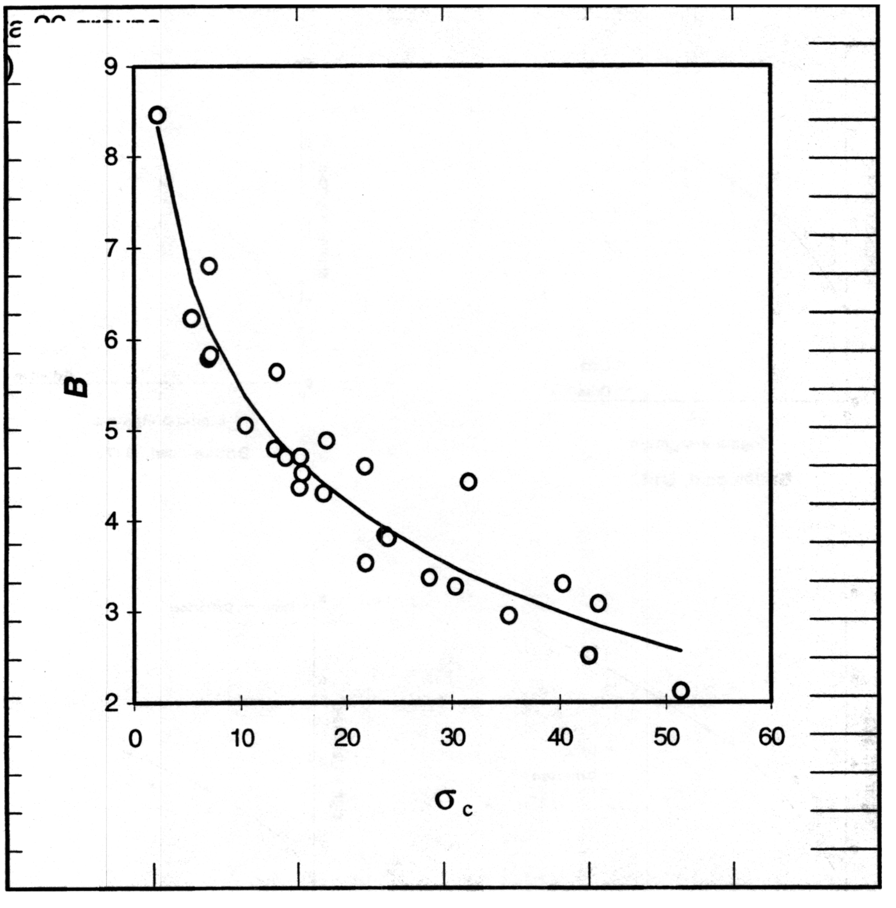

Fig. 5 Plot of *B* versus ρ_c in the Bieniawski's criterion for coal(α = 0.6)

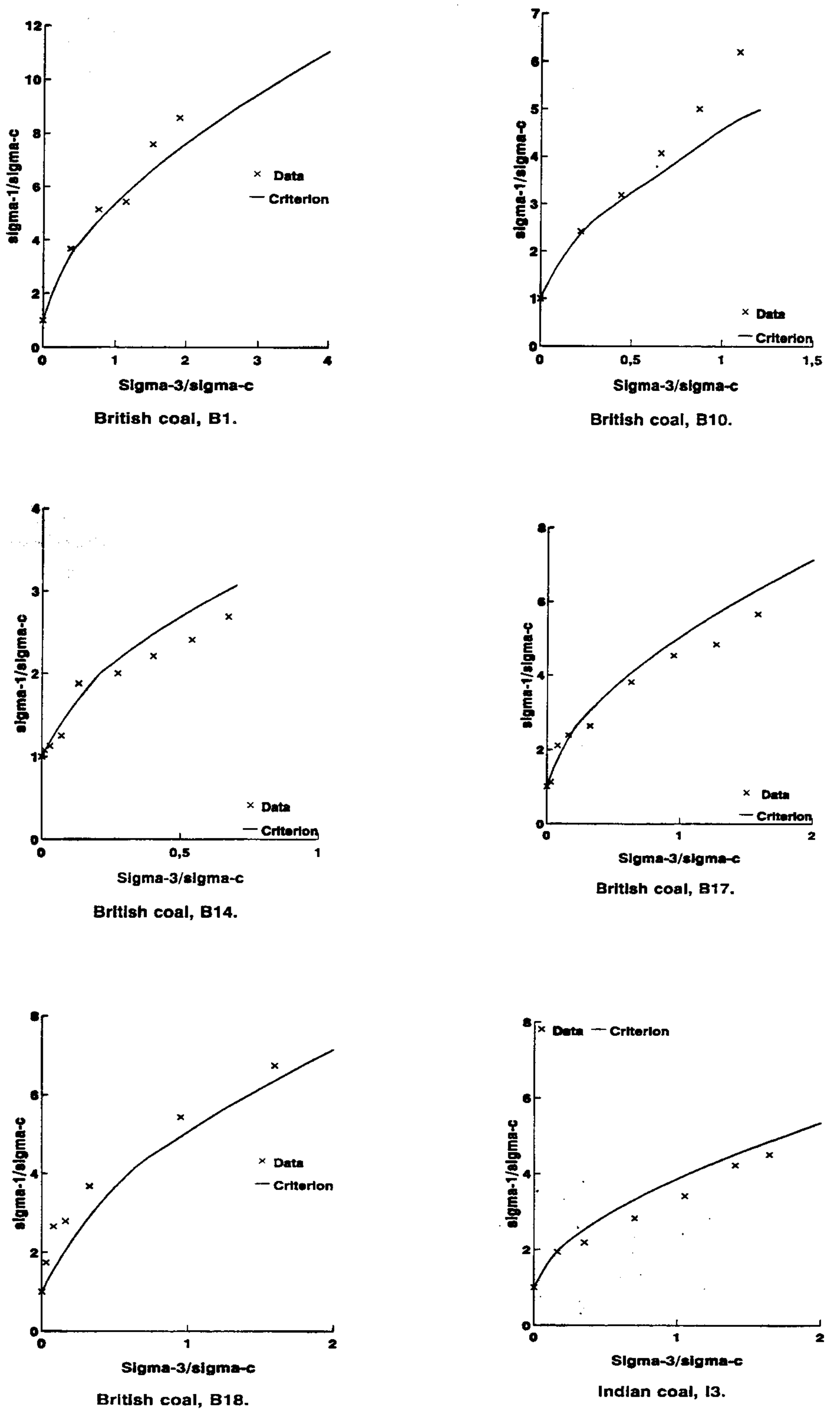

Fig. 6 The lowest correlative cases of the modified Bieniawski criterion.

Figs. 7 and 8 give the relationship between B in the Bieniawski criterion and ρ_c for limestone and granite as 2 examples.

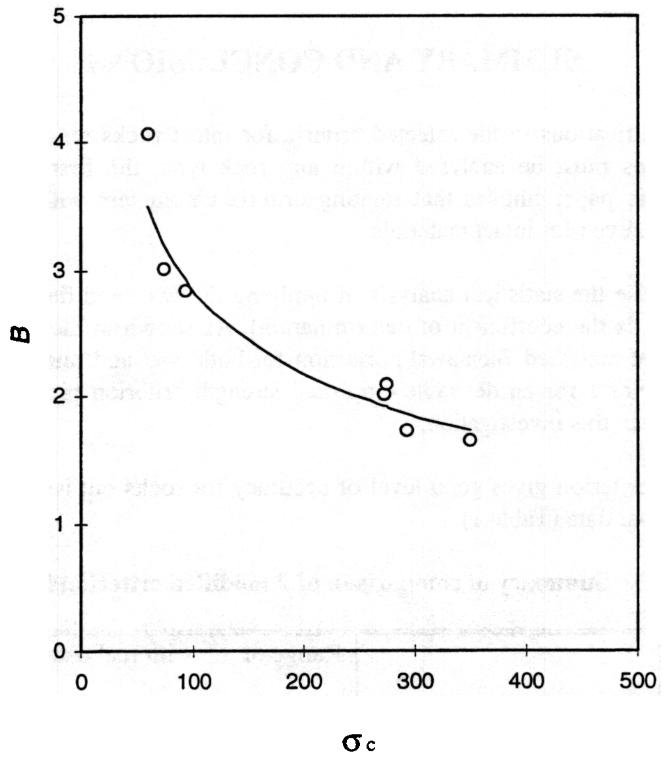

Fig. 7 Plot of *B* versus ρ_c for limestone and marble in the Bieniawski criterion[2]

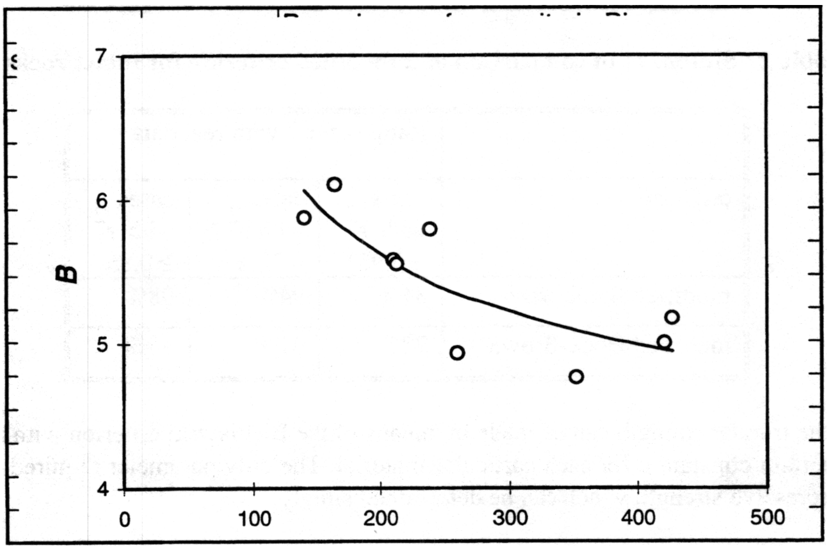

Fig. 8 Plot of *B* versus ρ_c for granite and granodiorite in the Bieniawski criterion[3]

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[2] $\alpha = 0.76$
[3] $\alpha = 0.65$

SUMMARY AND CONCLUSIONS

- Although eventual modifications to the selected criteria for intact rocks requires more investigations in which more proper data groups must be analysed within any rock type, the first conclusion coming out from the assessments done in this paper implies that treating criteria parameters with constant values would result in considerable inaccuracy, even for intact materials.

- Tables 1 and 2 summarise the statistical analysis of applying the two modified criteria to the laboratory data of coal and intact rocks(r^2 is the coefficient of determination). As shown in these tables, a significant accuracy is obtained by applying the modified Bieniawski criterion for both coal and intact rocks. This criterion, therefore, satisfies all the requirements for an desirable empirical strength criterion provided that it is amended with the modifications suggested in this investigation.

The modified Hoek and Brown criterion gives good level of accuracy for rocks but is not a suitable criterion for coal as shows low correlation with the coal data (Table 1).

Table 1 Summary of comparison of 2 modified criterion for coal.

	Range of r^2 with real data		
criterion	cases with $r^2 \geq 0.95$	cases with $r^2 \geq 0.90\%$	cases with $r^2 \geq 0.85$
modified Bieniawski	69%	92%	96%
modified Hoek-Brown	38%	58%	65%

Table 2 Summary of comparison of 2 modified criterion for intact rocks

	Range of r^2 with real data		
criterion	cases with $r^2 \geq 0.95$	cases with $r^2 \geq 0.90\%$	cases with $r^2 \geq 0.85$
modified Bieniawski	81%	94%	98%
modified Hoek-Brown	72%	91%	95%

- An estimate of the triaxial strength can be made by means of the Bieniawski criterion with a variable B dependent upon ρ_c and a certain constant ρ for each particular material. The only parameter required for this criterion is the unconfined compressive strength which can be determined simply.

- A strength criterion must be capable to deal with different conditions of a certain type of rock having different properties. Such a criterion may or may not provide the best estimation for a large number of mixed data from various collieries and seams around the world.

- In practice, a design engineer is faced with a certain type of rock with its particular properties. The characteristics of any rock type may change from place to place or even from one part to another part of the same seam or block. A criterion must be flexible enough to fit the various conditions of rock properties.

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