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# An approximate nonlinear modified Mohr-Coulomb shear strength criterion with critical state for intact rocks

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ABSTRACT

In this paper, the Mohr-Coulomb shear strength criterion is modified by mobilising the cohesion and internal friction angle with normal stress, in order to capture the nonlinearity and critical state concept for intact rocks reported in the literature. The mathematical expression for the strength is the same as the classical form, but the terms of cohesion and internal friction angle depend on the normal stress now, leading to a nonlinear relationship between the strength and normal stress. It covers both the tension and compression regions with different expressions for cohesion and internal friction angle. The strengths from the two regions join continuously at the transition of zero normal stress. The part in the compression region approximately satisfies the conditions of critical state, where the maximum shear strength is reached. Due to the nonlinearity, the classical simple relationship between the parameters of cohesion, internal friction angle and uniaxial compressive strength from the linear Mohr-Coulomb criterion does not hold anymore. The equation for determining one of the three parameters in terms of the other two is supplied. This equation is nonlinear and thus a nonlinear equation solver is needed. For simplicity, the classical linear relationship is used as a local approximation. The approximate modified Mohr-Coulomb criterion has been implemented in a fracture mechanics based numerical code FRACOD, and an example case of deep tunnel failure is presented to demonstrate the difference between the original and modified Mohr-Coulomb criteria. It is shown that the nonlinear modified Mohr-Coulomb criterion predicts somewhat deeper and more intensive fracturing regions in the surrounding rock mass than the original linear Mohr-Coulomb criterion. A more comprehensive piecewise nonlinear shear strength criterion is also included in Appendix B for those readers who are interested. It covers the tensile, compressive, brittle-ductile behaviour transition and the critical state, and gives smooth transitions.

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## 1. Introduction

The traditional Mohr-Coulomb shear strength criterion considers the strength to be linearly depending on the normal stress on the shear plane. It has been widely reported that the shear strength of many rocks actually follows a nonlinear relationship with the normal compressive stress, especially at extremely high confining pressure (e.g. Barton, 1976), and even at relatively low confining pressure (e.g. Mogi, 1974), if the rock is weak. The shear strength envelopes in the $\tau$-$\sigma_n$ plane are concave towards the normal compressive stress axis, where $\tau$ is the shear strength and $\sigma_n$ is the normal stress on the shear plane. Many nonlinear shear strength criteria exist in the literature, including the Barton criterion (Barton, 1976, 2013) and Hoek-Brown criterion (Hoek and Brown, 1980a, b, Hoek and Brown 1988). Barton (2013) summarised the nonlinear shear strengths for intact rocks, fractured rocks, jointed rocks and rockfills.

Mogi (1966) compiled a large body of triaxial experimental data for rocks from a variety of sources. Fig. 1 (from Barton (1976)) reproduces Mogi's test data for dry carbonate rocks and shows the variation of shear strength with the confining pressure. It can be seen that for most rock samples, the increase in the shear strength reduces and becomes negligibly small beyond a certain confining

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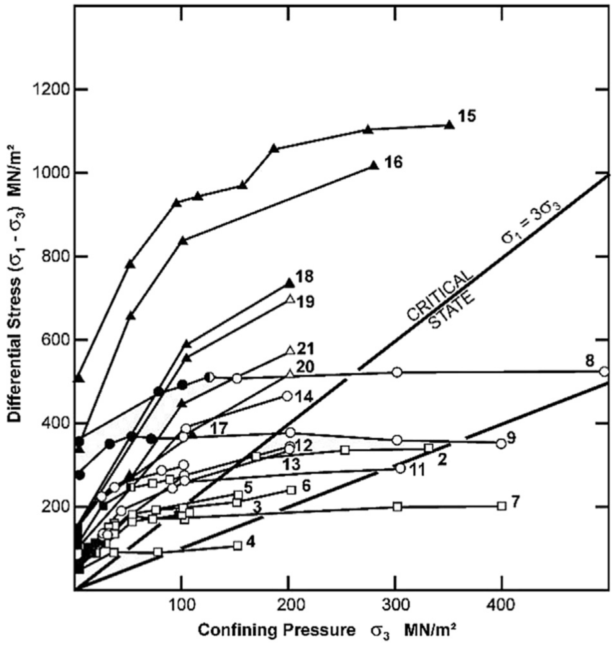


**Fig. 1.** Triaxial data for dry carbonate rocks compiled by Mogi (1966) in his Fig. 3. All tests were performed at room temperature. Brittle, brittle-ductile transitional and ductile behaviours are indicated by closed, half-open and open symbols, respectively. The numbers represent the type of rocks given in Mogi (1966). The two solid lines represent $\sigma_1 = 3\sigma_3$, the proposed critical state line of Barton (1976), and $\sigma_1 = 2\sigma_3$.

pressure. Mogi (1966)'s results also showed transition of behaviour from brittle to ductile.

Based on this and many other experiments in the literature, Barton (1976) proposed a critical state concept for rocks at which the tangent of the shear strength envelope approaches horizontal in the $\tau$-$\sigma_n$ plane (see Fig. 2, from Barton (2006, 2013)). Fig. 2 illustrates a shear strength envelope for intact rocks (solid curve) with the Mohr circles of stress states at four strength limit stages: uniaxial tensile strength (UTS), uniaxial compressive strength (UCS), brittle-ductile transition and critical state as well as the critical state line. The critical state line is also shown in Fig. 1. The dashed curve (denoted by J) in Fig. 2 represents the shear strength envelope for fractured rocks. At high confining pressure, for a given rock type, the two strength envelopes coincide, indicating that after the intact rock is fractured (reaching the ultimate strength), the stress will not drop and thus the rock mass behaves as a ductile material. A complete set of Mohr circles for high-pressure tests on strong limestones (with UCS of 250 MPa) derived from Byerlee (1968) data is shown in Fig. 3, reproduced from Barton (1976). From this, it can be seen that at the critical state, the major principal stress ($\sigma_1$) is about three times the minor one ($\sigma_3$). Furthermore, the minor principal stress (or critical confining pressure) is close to the UCS, and the value of peak shear strength is half of the normal compressive stress. These represent the quantitative aspects of the critical state concept for rock shear strength.

Singh et al. (2011) incorporated the critical state concept of Barton into a modified Mohr-Coulomb triaxial strength criterion for intact rocks, which was of quadratic form. Their analysis of data from a huge body of reported triaxial tests showed that the critical

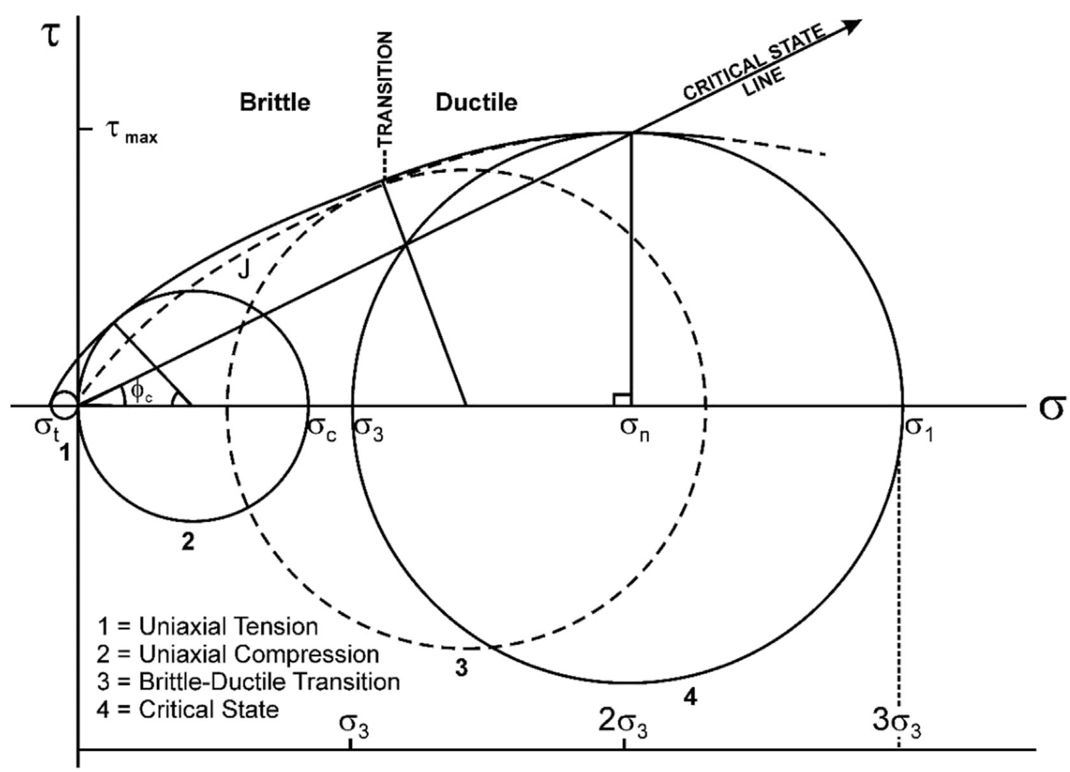


**Fig. 2.** Brittle-ductile transition and critical state of intact rocks, with Mohr circles for four strength limit stages, from Barton (1976, 2013). The critical state is at $\sigma_1 = 3\sigma_3$ with critical state internal friction angle $\varphi_c = 26.6°$. Curve "J" represents the shear strength of the rock when fractured, also for a given rock type. $\tau_{max}$ is the maximum shear strength at the critical state; $\sigma_t$ and $\sigma_c$ are the UTS and UCS, respectively.

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