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Prediction of Electric Load for Users Based on BP Neural Network

Siyi Liu [1, *], Runmin Wang [1], Yudong Fang [2]

[1] School of Resources and Environment, Henan Polytechnic University, Jiaozuo 454000, China
[2] School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China

Abstract: Rock masses in underground engineering are generally subjected to complex three-dimensional stress conditions rather than uniaxial loading. Therefore, triaxial compression testing has become a fundamental approach for investigating the strength, deformation, and failure behavior of rocks. In recent decades, extensive studies have been conducted on rock failure laws under triaxial compression, with particular attention to the effects of confining pressure, crack initiation and propagation, damage evolution, and macroscopic failure modes. Existing studies indicate that confining pressure not only increases the peak strength and residual bearing capacity of rocks, but also suppresses tensile crack growth, promotes shear localization, and drives the transition from brittle failure to ductile failure. In addition, the full failure process of rocks under triaxial compression is characterized by distinct stages, including crack closure, elastic deformation, stable crack propagation, unstable crack propagation, and post-peak failure. Acoustic emission monitoring, ultrasonic wave velocity analysis, and energy-based methods have further improved the understanding of progressive rock damage and failure mechanisms. This paper systematically reviews the current research on the strength evolution, deformation characteristics, failure modes, and major controlling factors of rocks under triaxial compression. On this basis, the limitations of existing studies are discussed, especially with respect to fractured rock masses, layered composite rocks, and complex stress paths. Future research directions are also proposed, including multi-method characterization, multi-field coupling analysis, and the integration of laboratory results with engineering-scale applications. This review may provide a useful reference for the study of rock mechanics and the stability evaluation of deep underground engineering.

Keywords: Rock mechanics, Triaxial compression, Failure law, Confining pressure, Crack propagation, Damage evolution.

1. Introduction

In underground engineering, such as deep mining, tunneling, underground caverns, and slope engineering, rocks are generally subjected to a three-dimensional stress state rather than uniaxial loading. Therefore, triaxial compression testing has become one of the most important approaches for investigating the strength, deformation, and failure behavior of rocks. Existing studies have demonstrated that confining pressure not only increases the peak strength of rock, but also suppresses tensile crack propagation, changes crack initiation and coalescence paths, and ultimately governs the transition from brittle failure to ductile failure [1-5, 8-12].

With the development of acoustic emission (AE), ultrasonic wave velocity monitoring, and energy analysis, research on rock failure under triaxial compression has gradually evolved from simple peak-strength characterization to full-process damage evolution analysis [1, 3, 5, 7, 9, 10]. Meanwhile, both domestic and international studies have established a relatively clear understanding of the effects of confining pressure, crack thresholds, and macroscopic failure modes. Nevertheless, the failure process of rock under triaxial compression is still affected by lithology, structural defects, and stress path, and a unified interpretation applicable to different rock types and engineering conditions has not yet been fully achieved [2-5, 10, 12-14]. Therefore, a systematic review of rock failure laws under triaxial compression is of great significance for both laboratory research and engineering applications.

2. Strength and Deformation Characteristics of Rocks under Triaxial Compression

(1) Strength evolution under confining pressure

One of the most fundamental observations in triaxial compression studies is that the peak strength of rock increases with increasing confining pressure. Hoek and Brown proposed a classical empirical strength criterion, showing that the strength envelope of intact rock and rock mass under triaxial stress usually exhibits a nonlinear relationship rather than a simple linear increase [8]. This indicates that the strengthening effect of confining pressure is not merely an external confinement effect, but is closely related to crack closure, crack propagation inhibition, and delayed localization of damage.

Experimental studies on different rock types have further confirmed the controlling role of confining pressure. Wang et al. found that, with increasing confining pressure, sandstone exhibits higher peak strength and noticeable changes in deformation modulus and dilatancy characteristics, indicating that confining pressure significantly influences both the deformation behavior and the damage mechanism of sandstone [2]. Wen et al. reported that for slate, higher confining pressure delays the onset of abrupt damage evolution and alters the accumulation and dissipation of strain energy during loading [3]. Zheng et al. also observed that in coral skeletal limestone, the macroscopic failure pattern gradually changes from tensile splitting to oblique shear with increasing confining pressure, suggesting that confining pressure modifies not only the strength level but also the dominant failure mechanism [4].

Therefore, the role of confining pressure should be understood not simply as raising the peak stress, but as fundamentally changing the internal crack evolution process and the overall load-bearing mechanism of the rock [2-4, 8].

(2) Full-process deformation and damage characteristics

Under triaxial compression, the deformation and failure process of rock usually includes crack closure, quasi-elastic deformation, stable crack growth, unstable crack growth, and post-peak failure [9, 10]. Martin and Chandler showed that substantial internal damage accumulation already occurs before the peak strength is reached, indicating that the peak point is not the onset of cracking, but rather the critical state at which cracks rapidly coalesce and localize [9]. Cai et al. further introduced the concepts of crack initiation stress and crack damage stress, which provide a more effective description of the progressive transition from stable deformation to unstable failure in brittle rocks [10]. Hoek and Martin summarized these phenomena in their review of fracture initiation and propagation in intact rock [12].

Domestic studies have further characterized this process through AE, wave velocity, and energy methods. Yang et al. suggested that rock damage under triaxial compression can be divided into initial damage, stable development, accelerated development, and final failure stages, and that confining pressure reduces AE activity during the crack-closure stage while enhancing the post-peak bearing capacity [1]. Zhang et al. combined AE and ultrasonic wave velocity measurements to identify crack closure stress, crack initiation stress, and crack damage stress in sandstone, and found that failure mode shifts from splitting–shear failure at low confining pressure to dominant shear failure at high confining pressure [5]. Chen also reported that AE activity corresponds well to the deformation stages of rock under triaxial compression, especially during the transition from stable deformation to accelerated failure [7].

Energy-based analysis provides another perspective on the progressive failure process. Wen et al. found that both elastic energy accumulation and dissipated energy release vary significantly with confining pressure, and that higher confining pressure enhances the energy storage capacity of rock before failure [3]. Zheng et al. also observed a sharp increase in cumulative ringing counts and AE energy when the stress level reached about 90% of the peak strength, which can be regarded as the onset of unstable crack propagation [4]. These findings indicate that rock failure under triaxial compression is not an instantaneous event at peak stress, but a gradual process of damage accumulation and crack coalescence [1, 3-5, 9, 10].

3. Failure Modes and Major Controlling Factors under Triaxial Compression

(1) Evolution of failure modes under different confining pressures

Confining pressure is the key factor controlling the evolution of failure modes in rocks. Wawersik and Fairhurst demonstrated that brittle rocks under low confining pressure usually experience a rapid post-peak stress drop and exhibit pronounced sudden brittle failure, whereas under higher confining pressure, the post-peak response becomes much gentler and the residual load-bearing capacity is enhanced [11]. Hoek and Martin further pointed out that the formation of a macroscopic shear band in intact rock is not the result of pure shear alone, but rather the consequence of tensile crack initiation, propagation, interaction, and eventual localization [12]. This means that confining pressure changes not only the stress magnitude but also the dominant cracking mechanism and the final macroscopic failure pattern [11, 12].

Based on both Chinese and international studies, the failure-mode evolution of rock under triaxial compression can be summarized as follows: at low confining pressure, rocks mainly exhibit axial splitting or tensile–shear mixed failure; at intermediate confining pressure, tensile crack growth is suppressed and single-shear or conjugate-shear failure becomes dominant; at high confining pressure, crack localization becomes more prominent and the rock tends to fail in a compressive–shear mode or even display certain ductile-flow characteristics [4, 5, 9 11, 12]. Zhang et al. clearly showed that sandstone tends to undergo splitting–shear mixed failure at low confining pressure and shear failure at high confining pressure [5]. Similarly, Zheng et al. reported that the failure surface of coral skeletal limestone evolves from stepped tensile-dominated fractures to a single inclined shear band as confining pressure increases [4].

The brittle-to-ductile transition can also be inferred from AE evolution and post-peak behavior. Yang et al. found that confining pressure increases the post-peak bearing capacity of limestone and delays the occurrence of the major AE burst relative to the final macro-failure [1]. Cao et al. also showed that AE event counts, peak distributions, and damage development characteristics of coal-rock specimens vary significantly with confining pressure, with failure becoming more progressive at higher confinement [6]. Therefore, the effect of confining pressure on failure mode can be interpreted as a comprehensive regulation of crack density, crack type, and crack coalescence rate [1, 6, 11, 12].

(2) Major controlling factors of rock failure under triaxial compression

Besides confining pressure, lithology, structural defects, and stress path also play important roles in controlling rock failure under triaxial compression. Different rock types differ in mineral composition, grain structure, cementation strength, and the development degree of initial microcracks, and thus exhibit different crack initiation thresholds, damage thresholds, post-peak softening characteristics, and sensitivity to confining pressure [2-5, 9, 10, 12]. For example, sandstone studies often focus on dilatancy and crack-threshold identification [2, 5], slate studies highlight energy dissipation and damage evolution [3], whereas coral skeletal limestone shows pronounced confining-pressure-dependent fracture transformation and pre-peak energy mutation [4]. This suggests that rock failure laws under triaxial compression have both common features and strong lithological dependence.

Structural defects and pre-existing fractures alter the local stress concentration pattern and provide preferential paths for crack propagation, making fractured or layered rocks more likely to fail locally at relatively low stress levels. Zhang et al. found that shear-wave velocity is more sensitive to damage than compressional-wave velocity, and is therefore more suitable for identifying pre-peak characteristic stresses associated with crack development [5]. Chen and Yang et al. also showed that AE responses are closely related to deformation-stage transitions and can be used to identify the transition from stable crack growth to unstable crack propagation [1, 7]. Thus, combining structural effects with monitoring parameters provides a more meaningful interpretation of failure mechanisms than simply comparing peak strength [1, 5, 7].

Stress path is another important factor. Su et al. reported that coal specimens under different stress paths exhibit significantly different AE characteristics during deformation and failure, indicating that loading and unloading paths can substantially alter crack development and damage evolution [13]. From a theoretical perspective, Al-Ajmi and Zimmerman pointed out that the traditional Mohr–Coulomb criterion does not adequately account for the intermediate principal stress, whereas the Mogi-type criterion is more suitable for describing rock failure under multiaxial stress conditions [14]. This implies that although conventional triaxial compression tests reveal many essential laws, more attention should be paid to intermediate principal stress effects and complex stress paths in deep underground engineering.

4. Conclusions and Perspectives

A review of the existing literature indicates several widely accepted conclusions. First, confining pressure is the primary factor controlling rock failure under triaxial compression. It not only increases peak strength and residual bearing capacity, but also suppresses tensile crack propagation and promotes the transformation of failure mode from brittle to ductile [2-5, 8, 11, 12]. Second, the triaxial compression process is highly progressive, involving crack closure, crack initiation, stable propagation, unstable propagation, and final macro-failure [1, 3, 5, 9, 10, 12]. Third, AE, wave velocity, and energy analysis have become important tools for identifying characteristic stresses, detecting failure precursors, and interpreting failure mechanisms [1, 3-7].

However, current studies are still mainly based on intact and relatively small laboratory specimens. Research on fractured rock masses, layered composite rocks, and complex unloading stress paths remains insufficient. Future work should therefore focus on three aspects: comparative studies on different lithologies and structural conditions, multi-method characterization combining AE, CT, ultrasonic testing, and energy evolution, and the connection between conventional triaxial tests, true triaxial tests, and in situ engineering conditions [4, 5, 10, 12-14].

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