Research and prospect of post-peak strain-softening characteristics of rocks

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Abstract. The current research status and development trends are summarized in order to analyze the strain softening deformation characteristics of post-peak of rocks, and the corresponding key problems are found, the key issues included the influence of strain softening on tunnel engineering and the research status of strain softening in hydraulic engineering. Based on the existing researches, it is found that there are few studies on the deformation characteristics of post-peak of rocks, and there is a lack of damage constitutive model which can better describe the post-peak mechanical properties. At present, it is impossible to simulate the influence of rock softening on stiffness degradation in indoor tests, and there is also a lack of on-site construction measured data as support; at the same time, the surrounding rock control and protection technology under loading and unloading also urgently needs to be improved; in addition, the interaction mechanism between water and structure during rock softening with water needs to be further explored.

1. Introduction
As a kind of geological material with complex mechanical properties, after a long diagenesis process, the rock has formed different shapes and randomly distributed micro-cracks and pores, showing the characteristics of heterogeneity and anisotropy. In recent years, with the continuous development of underground engineering to the deep, rocks are susceptible to high ground stress, high ground temperature, high karst water pressure and mining disturbances. On the one hand, in rock mass engineering excavation, the surrounding rock is often in the post-peak deformation stage. With the development of deformation, the rock mass may suddenly lose stability, causing economic losses and casualties. On the other hand, because the deformation characteristics of rock are obviously different from that of metal materials, especially in the post-peak deformation stage, the mechanical behavior of the rock is difficult to describe with the classical strength theory due to the uncertainty of the way the stress falls. Therefore, the research on the post-peak strain softening deformation characteristics of rock has important theoretical and practical significance for engineering.

Generally speaking, when the stress of the rock reaches the peak strength, as the deformation continues to increase, the phenomenon that its strength drops sharply is called "strain softening". For a
long time, the strain softening characteristics of rock have attracted the interest and attention of many scholars, and it has always been a research hotspot of rock mechanics workers. From the perspective of overall research ideas, these studies can be divided into two categories: The first category is to study the mechanism of rock strain softening characteristics after the peak from the microscopic perspective of the expansion and penetration of rock fractures. They believe that when strain softening occurs, the internal deformation of the rock is not uniform, and obvious local strain will occur in the shear zone \cite{1-2}. The second category is from the perspective of the macroscopic effect of rock strain softening, combined with continuum theory, to establish a rock plastic strain softening mechanical model to study its softening mechanical properties \cite{3}.

The above research results provide important research ideas for engineering applications, provide an important theoretical basis for solving tunnels, mining, water conservancy and other engineering design, and also provide important parameters for slope stability analysis and important engineering early warning.

In order to better understand the research status and progress of the above problems, the author summarizes and analyzes the research on the post-peak strain softening characteristics of rock. On the basis of previous researches, it discusses the current problems in this field, and puts forward some views on future research directions.

2. Impact of post-peak rock strain softening on tunnel (mining) engineering

With the economic development of our country and the further acceleration of urbanization, the use of underground space has gradually entered people's field of vision, and underground projects have continued to move deeper. According to research, for roadways, the surrounding rock often undergoes strain and soft changes during the excavation and unloading process, which inevitably triggers the deformation of the surrounding rock of the tunnel and the roadway, resulting in stress concentration, and endangering the safety of underground construction operations. Considering that the deep rock masses are mostly in various high-stress engineering geological environments, the impact analysis of the post-peak should change on tunnel engineering and mining engineering will be extremely complicated. At present, research methods based on theoretical analysis, laboratory experiments and numerical simulation have produced more research results.

2.1. Theoretical analysis

At present, the theoretical research on surrounding rock deformation caused by strain softening of tunnel surrounding rock is mainly the establishment of elastoplastic softening model. In the early days, scholars Nayak and Zienkiewicz \cite{4} proposed the elasto-plastic strain softening constitutive relationship in 1972, and Sharan \cite{5} gave the analysis of the strain softening model based on the Hoek-Brown elasto-brittle plastic model in the stress-strain process of surrounding rock formula. Wang Xuebin\cite{6} studied the post-peak deformation characteristics of rocks based on the gradient plasticity theory, and proposed the deformation characteristics of rock samples under shear failure conditions.

In recent years, scholars Yuan Wenbo and Chen Jin \cite{7} established an elastoplastic softening model based on the strain softening characteristics of rock masses, and analyzed the mechanical properties of the plastic zone and fracture zone of the surrounding rock. It is also pointed out that the degree of softening of the rock mass and the magnitude of the residual strength have a significant impact on the stress distribution and stability of the surrounding rock. On this basis, Fu Guobin \cite{8} comprehensively considered the rock strain softening characteristics, introduced the softening modulus, and derived the universally significant theoretical analytical solution for the failure range and displacement of the surrounding rock of the roadway. Studies have shown that the degree of strain softening of the surrounding rock has an important impact on the fracture range, which affects the convergence of the surrounding rock of the roadway and causes large deformation of the surrounding rock. Furthermore, Chen Liang \cite{9} established the softening model and residual model based on the Drucker-Prager criterion and the non-associated flow law, while considering the post-peak strain softening
characteristics of the surrounding rock, and introducing the softening modulus. The influence of different yield criteria and surrounding rock parameters on the state of surrounding rock is analyzed. The analysis shows that the increase of support resistance and the decrease of surrounding rock softening modulus are effective methods to restrain the deformation of surrounding rock.

Krajcinovic and Silva [10-11] and Cao Wengui [12] established a unified damage statistical constitutive model that can reflect the entire process of rock strain softening and deformation under different confining pressures based on the randomness of the distribution of defects contained in rock materials. They studied the deformation characteristics and damage evolution of rocks under different confining pressures, and proposed a method for determining the parameters of the strain softening statistical constitutive model.

Generally speaking, some progress has been made in studying the deformation and failure mechanism of surrounding rock strain softening and unstable expansion and fracture. However, considering the complexity of the mechanical process itself, the development of theoretical models is limited. Especially in the process of theoretical derivation, many simplifications and assumptions were made on the softening law of rock mechanical parameters after the peak, and the influence of confining pressure on the mechanical parameters (cohesion and internal friction angle) of the rock after the peak was not considered, so it is quite different from the actual situation.

2.2. Indoor test

In terms of indoor tests, in recent years, scholars from all over the world have carried out a large number of triaxial tests on the softening characteristics of various types of rocks (see Table 1):

| Source | Brief description of test content | Main conclusion |
|--------|----------------------------------|----------------|
| Reference 13 | The limit value of rock transition from brittleness to ductility was clarified. | The rock mass with reduced confining pressure near the underground project will mainly undergo strain softening behavior. |
| Reference 14 | The mechanical properties of rock under triaxial compression were studied. | The main parameters required by the strain softening model were cohesion, internal friction and expansion angle, and elastic constants. |
| Reference 15 | The focus was on the relationship between the peak strength of the rock and the confining pressure under the triaxial test. | When the rock mass is at its peak strength under low confining pressure, the partial loss of cohesive force causes local deformation and strain softening behavior, resulting in a great stress drop. |
| Reference 16 | The post-peak failure behavior of rocks under triaxial and true triaxial tests was studied. | The strain hardening, strain softening and plastic behavior of rock depend on the stress state. |

The above research shows that the confining pressure is an important factor affecting the post-peak strain softening of the rock. With the increase of confining pressure, the elastic modulus, yield stress, peak strength, residual strength, strain hardening degree at peak, and ultimate strain of rock all have an increasing trend.

Lu Yinlong [17] carried out an indoor triaxial compression test on weak rock masses, and obtained the stress-strain full-process relationship curves of rock masses under different confining pressures (see Figure 1). It can be seen from the figure that under low confining pressure, the post-peak stress of the rock undergoes a brittle drop. As the confining pressure increases, the post-peak plastic deformation capacity increases, and the peak strength and residual strength increase correspondingly, and show a certain degree regularity. Then, based on the assumption of Mohr-Coulomb limit failure, the coupling relationship between generalized cohesion, generalized internal friction angle, confining
pressure, and equivalent plastic shear strain was established. On this basis, the experimental data is used to analyze the post-peak strain softening mechanical properties of the rock, and then the effect of confining pressure on the post-peak rock strain softening process is well simulated. Zhang Fan[18] conducted conventional triaxial tests on the Three Gorges granite, and analyzed the relationship between granite strength parameters and post-peak strain softening parameters based on elastoplastic theory, and established a post-peak strain softening model for granite.

![Figure 1. Complete stress-strain curves of granite under different confining pressure.](image)

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Li Wenting [19] carried out a triaxial compression test on marble, and based on the Mohr-Coulomb strength criterion, with the internal friction angle $\phi$ as the intermediate variable of the strain function, the post-peak non-linear stress-strain relationship of the rock mass was established. Then, by establishing the expression of the post-peak elastic modulus of the rock mass, after numerical calculation and fitting, the post-peak stress-strain relationship curve of the marble without confining pressure is obtained.

Zhang Chunhui [20] took a sample of Xinjiang Balikun sandstone to conduct a triaxial compression test indoors, and obtained the stress-strain relationship curve of the whole process. A new parameter describing the influence of confining pressure on the post-peak brittleness of rock is proposed, namely the brittle modulus coefficient. Based on the brittle modulus coefficient and strength degradation index, a rock strain softening model considering the influence of confining pressure is established. The test results show that as the confining pressure increases, the post-peak residual strength of the rock increases and the volume expands; as the axial strain increases, the rock undergoes elastic compression and the void space decreases.

Although the above-mentioned experimental research has achieved many results, there are still many problems. For example, the construction of the post-peak strain softening model is too complicated, and it needs to be simplified and assumed. However, in the course of the experiment, some phenomena that are inconsistent with the hypothesis will inevitably occur. For example, when the rock has stiffness degradation after the peak, it does not conform to the assumption that the post-peak unloading process is linear elastic, which leads to the deviation of the conclusion from the experiment and the actual situation, so it is difficult to be widely used in actual engineering.

2.3. Numerical simulation

The use of numerical calculation software to study the mechanical properties of rock and its constitutive relationship is an extremely important research method, which can verify the established model from an ideal level. Numerical simulation methods can accurately simulate the forces and deformations of the projects built in the rock in the three-dimensional state through calculations. It can also simulate and analyze the influence of tunnel surrounding rock excavation and support schemes on...
the stability of surrounding rock under complex boundary conditions, which is very suitable for simulating complex nonlinear rock mass excavation processes.

Yang Chao [21] used curve fitting theory to analyze and study the relationship between confining pressure and post-peak rock strain softening parameters, and established a post-peak strain softening numerical model. Wang Hongying [22] analyzed the deformation mechanism of post-peak strain softening of the rock mass, and used FLAC3D to numerically simulate the stress and deformation state of the surrounding rock in the underground chamber, and described the complete state of the surrounding rock through the failure proximity index. The research results show that the zone fracture is closely related to the post-peak deformation characteristics of the rock mass.

Su Yonghua and Zheng Xuan [23] proposed that the stress-strain relationship obeys the post-peak strain softening model based on the characteristics that the mechanical properties of the surrounding rock of deep underground engineering are significantly reduced under the action of excavation and unloading. And use FLAC3D numerical software to reproduce the partition fracture phenomenon of surrounding rock. The simulation results show that: under certain conditions, the smaller the critical plastic softening coefficient, the more obvious the partition rupture phenomenon.

On this basis, Sun Chuang [24] believed that the post-peak behavior of the rock mass has a greater influence on the confining pressure, and the plastic softening coefficient will change with the change of the confining pressure during the post-peak unloading process. Cui Lan [25] used only constant or linearly varying dilatancy models to derive the strain-softening surrounding rock stress-strain field of deep-buried circular tunnels. A finite difference method that can reasonably consider the non-linear dilatancy effect of surrounding rock and its strain softening characteristics is proposed. The research results show that the deformation of surrounding rock is mainly controlled by the confining pressure under the condition that the geological strength index (GSI) is small and the applied supporting resistance is relatively small.

In summary, the existing numerical simulations mostly use the finite difference method and the numerical simulation software FLAC3D for numerical calculations. Although the simulation results are in good agreement with the actual situation, there are still a series of problems: In numerical simulation, most of the input data is a method of obtaining special values, and the accuracy of the results needs to be improved; another example is when the numerical simulation of large-scale projects is performed, the calculation efficiency is too low, which leads to the calculation time is too long.

3. Surrounding rock deformation control technology

3.1. Control and protection mechanism

In order to protect the safety of tunnels and underground construction, the deformation of surrounding rock caused by the strain softening and capacity expansion caused by the excavation and unloading of the load in the project. In addition to a large number of theoretical studies on the stability mechanism of surrounding rocks, a series of control and protection technologies have gradually formed.

In the roadway, the research methods of the surrounding rock deformation mechanism can be roughly divided into two types: elastic analysis and elastoplastic analysis.

According to the generalized concept of plasticity, researchers have done a lot of experiments and research on elastoplastic solutions. Fenner, Castner calculated the stresses in the elastic zone and plastic zone of the roadway based on the elastoplastic model, and obtained the famous Castner formula (used to find the radius of the plastic zone). However, in the calculation, the deformation characteristics of the rock material itself are ignored. They treat the rock mass as an ideal elastoplastic medium, so the results are often inconsistent with the actual situation.

In recent years, scholars have conducted a large number of experiments and theoretical studies on rock masses, and studies have shown that rock masses have obvious strain-softening deformation characteristics. When the stress exceeds its ultimate compressive strength, its ultimate strength will drop sharply until it drops to the residual strength. Brown [26] used the strain softening characteristics of the rock mass to calculate the stress of the surrounding rock. Yuan Wenbo and Chen Jin [13] used the
elastoplastic softening model to analyze the mechanical form of the plastic zone and the broken zone of the surrounding rock based on the strain softening characteristics of the rock mass, and deduced the calculation formula of the radius \( R \) of the plastic zone and the broken zone:

\[
R = \frac{a}{\beta + 1} \left[ \frac{2}{K_p + 1} \left( \frac{P_0 + \frac{\sigma_c + \beta B_c}{K_p - 1}}{K_p - 1} \right) \frac{1}{K_p - 1} \right]^2 - \frac{2}{K_p + 1} \left( \frac{\sigma_c - \sigma_r + \beta B_c}{K_p - 1} \right) \frac{1}{K_p - 1}
\]

The above research shows that the strain softening of the rock mass has a huge impact on the mechanical properties of the surrounding rock and the stability of the roadway.

Jiang Binsong \[27\] divided the surrounding rock of the roadway into a fracture zone, a plastic zone and an elastic zone (see figure 2), and based on the Mohr-Coulomb criterion and the non-associated elastoplastic flow criterion, they obtained a closed analytical solution of its stress and deformation. And determine the analytical formula of the radius of the fracture zone and the plastic zone of the surrounding rock.

![Analytic model of a circular tunnel.](image)

According to the deformation characteristics of rock materials, Pan Yang \[28\] introduced parameters that have a certain influence on the surrounding rock of the roadway. Using a rock stress-strain three-stage mechanical model, the mechanical properties of the elastic zone, plastic softening zone and plastic residual zone of the surrounding rock of a circular roadway under a non-uniform stress circle are analyzed. The theoretical solution of elastoplasticity of circular tunnels under non-uniform stress field is derived. And on this basis, the influence of strain softening on the surrounding rock of the roadway is analyzed. The results show that the strain softening of the rock has a great influence on the mechanical form of the surrounding rock and the size of the plastic zone; with the decrease of the softening modulus, the radius of the plastic zone also decreases.

Chen Jin and Yuan Wenbo \[29\] discussed the rock mass structure with strain softening of the rock mass, and carried out an elastoplastic analysis of the surrounding rock of the roadway by using the limit equilibrium method. Ma Nianjie and Zhang Yidong \[30\] obtained the elastoplastic solution of the surrounding rock of the roadway considering softening based on the analysis of the full stress-strain curve of the rock mass. Wang Shuilin \[31\] used the characteristic that the strength of strain softening
material decreases with the increase of plastic strain, and transformed the simulation of strain softening behavior into a series of analysis of brittle plastic process to study the surrounding rock of the roadway.

Judging from the above-mentioned research status, although researchers have conducted certain theoretical studies and put forward many effective solutions for the post-peak stability of surrounding rock masses, there are still many shortcomings: For example, most of the current studies are carried out on the basis of the Mohr-Coulomb criterion, ignoring the influence of the intermediate principal stress, and the test proves that when the strength of the rock takes the influence of the intermediate principal stress into consideration, its strength will increase by about 30% [32].

3.2. Control and protection technology
Under the combined influence of ground pressure, strong mining and complex geological conditions, the surrounding rock of the roadway will undergo large nonlinear deformations such as strain softening and capacity expansion. Therefore, how to effectively control the surrounding rock deformation and ensure its stability has always been a research hotspot. Except for the ability of surrounding rock to resist deformation, the supporting structure is an important tool for maintaining stability. Using bolts and shotcrete to reinforce the surrounding rock of the cavern to control the deformation of the surrounding rock, a lot of research results have been obtained in the research of engineering practice problems that produce deformation, especially the use of bolt support. Because of its advantages in improving the stress of surrounding rocks, increasing the strength of surrounding rocks, and reducing support costs, it has been widely used in the excavation and support of tunnels and mining projects.

Li. C and Stillborg B [33], Y. Cai [34] studied the interaction mechanism between grouting bolts and surrounding rock. The analytical solutions of the deformation, strain, and radius of the plastic zone of the surrounding rock under the bolt support are solved by the coordination of the displacement and deformation of the bolt and the rock mass. Lang [35] used gravel self-bearing slab test and two-dimensional photoelasticity test and found that under certain conditions, the bolt and the surrounding rock can form a bearing structure with a certain bearing capacity, and proposed the principle of the compression band of the bolt, and confirmed the existence of the arched compression zone (see figure 3). The shaded part in the figure represents the compression zone formed by the anchor rod pressure, and the blocks in the compression zone will be locked to each other to form a self-supporting arch structure.

![Figure 3. Figure sketch of bolts compression zone](image-url)
Wen Jingzhou [36] analyzed the stress distribution and change characteristics of the anchoring surface of the full-length bonded anchor in the surrounding rock elastoplastic medium. Based on the force balance of the micro-segment bolt and the mechanical transmission mechanism of the shear stress of the anchoring interface, a differential equation for the displacement of the bolt is established. The differential equation is solved, and the analytical solutions of shear stress and axial force of the anchoring interface bolt under the interaction of the anchor bolt and the axial force are obtained. Hou Chaojiong and Gou Panfeng [37-39] put forward the theory of strengthening the strength of surrounding rock that may lead to strain softening (see table 2).

| Source       | Brief description of test content                                                                 | Main conclusion                                                                 |
|--------------|--------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Reference 37 | The strengthening effect of roadway bolt support on the peak strength and residual strength of the rock mass in the anchoring range (see figure 4). | 1) Bolt support is essentially to form a structure with a certain bearing capacity through the interaction between the bolt and the rock mass, that is, the anchor solid; 2) Bolt support can improve the mechanical properties of the anchored rock mass by improving the mechanical parameters of the anchored rock mass. |
| Reference 38 | The deformation and strength characteristics of the anchor are studied, and then the supporting mechanism of the bolt is analyzed. | The peak strength, post-peak strength and residual strength of the rock mass in the anchoring area of the bolt can be significantly improved after being anchored. |
| Reference 39 | The mechanical characteristics and production geological conditions of coal roadway surrounding rock under various difficult and complex conditions are studied. | Bolt support can effectively strengthen the strength of the surrounding rock that may soften and maintain its stability. It can increase the bearing capacity of the surrounding rock by changing the stress state of the surrounding rock and improve the support condition of the roadway. |

![Figure 4. Shape and dimension of separated rock body supported by bolt.](image)

Carranza-Torres [40] verified through numerical simulation that the bolt can reduce the deformation of the rock mass around the tunnel and increase the confining pressure of the surrounding rock of the tunnel. Chen Xiaoxiang [41] used Flac3D software to study the deformation characteristics of the surrounding rock of the mining roadway under high stress conditions. Taking the return air tunnel of a working face as the research object, they analyzed the deformation factors of the return air port and...
proposed a high prestress and high strength anchor. The overall idea of the coordinated support of rods and anchors, and the field test results show that the technology can achieve better results.

It can be seen from the above research that the existing roadway surrounding rock control technology mostly uses high-strength bolts and anchor cables for combined support. However, the load-bearing law in the actual supporting process of anchor rods and anchor cables is still unclear, and the coordination mechanism of the two is difficult to determine, and researchers need to pay close attention to it.

4. Influence of post-peak rock strain softening in water conservancy projects

With the implementation and construction of various large-scale hydropower projects, more and more rock-related problems continue to emerge. In addition to considering the mechanical properties of the rock under excavation and unloading, it is also necessary to pay attention to the problem of rock softening in contact with water. After the rock encounters water, the strength will decrease and the deformation will increase, which will cause instability and failure. Therefore, the study of water softening has very important theoretical significance and practical value.

4.1. Understanding of softening mechanism

The softening of rock when it meets water means that when the rock encounters water, various physical and chemical reactions occur, which leads to changes in the microstructure of the rock, thereby changing the physical and mechanical properties of the rock, and ultimately reducing the strength of the rock and increasing its deformation.

Zhou Cuiying and Tan Xiangshao [42] used scanning electron microscopy, powder crystal ray diffraction, and rock physical mechanics to determine the microstructure and physical and mechanical properties of rocks, and discussed the softening mechanism and dynamic changes of rocks. The study of Ballard and Beare [43] showed that the disintegration and softening of physicochemical soft rock is the water-rock chemical effect of soft rock. Yang Chunhe [44] conducted triaxial compression tests on water-soaked slate, and analyzed the process and mechanism of slate softening in contact with water. Various physical parameters such as the wetting angle and water absorption rate of the slate in the water immersion process were measured by various instruments such as polarized light microscope and electronic scanning electron microscope.

Most of the research on the mechanism of rock softening focuses on the interaction of the rock with water, which leads to the change and accumulation of the internal microstructure of the rock, and finally leads to the decrease of its macro-mechanical properties.

4.2. Effect of water on softening

The softening effect of water on the rock mass is the main reason for the decrease of the physical and mechanical properties of the rock mass. Scholars from various countries have analyzed and studied the process of water-rock interaction. Studies have shown that the process of water-rock interaction is a comprehensive process of physics, chemistry and mechanics. In addition, the structural changes of rocks before and after encountering water are also the focus of research by researchers. A large number of experiments and theoretical studies have been carried out on them. The representative results are as follows:

Hadizadeh J [45] analyzed and studied the softening effect of water on sandstone, and proposed that the water-rock effect is mainly related to the size and shape of the pores in the sandstone, the composition of the cement and other factors. Tang Liangsheng and Zhou Cuiying [46] discussed the mechanism of rock water chemical damage and its quantification method, and summarized the research progress on the effect of hydrochemical solutions on the macro-mechanical properties of rocks. Vasanthi and Van [47] analyzed and studied the characteristics of rock strength reduction after exposure to water. They tested the uniaxial compressive strength of limestone in dry and saturated states. The results showed that the strength of limestone was reduced by approx 34%.
Most of the above researches on the softening of rocks by water are concentrated on the chemical effects of water-rock interaction. The damage to the structure caused by the action of water and rock causes the decline of the physical and mechanical properties of the rock. The direct cause is the destruction of the internal structure of the rock. At present, the research on the interaction mechanism between water and structure in rock softening is relatively single, and it has not been studied on different scales.

5. Deficiencies and prospects
To sum up, although a lot of research results have been made on the post-peak strain softening and deformation characteristics of rocks, there are still many problems. The author puts forward some issues and further research directions that need to be explored in the current research. The main contents are as follows:

1) Theoretical aspect: It can be seen from the research status that scholars around the world have conducted certain theoretical studies on the post-peak mechanical behavior and residual phase mechanical properties of rocks. A series of post-peak stability problems related to the surrounding rock mass of the tunnel have been solved, and many effective solutions have been provided. However, the current researches on the post-peak characteristics of rocks mostly focus on the period from the peak to the residual deformation stage, and there is insufficient research on the mechanical characteristics of the residual stage. It is mainly manifested in that there is little understanding of the generation of rock bearing capacity, deformation parameters and strength in the residual stage, and how to make full use of the residual stage bearing capacity to control the stability of the surrounding rock. And the lack of a constitutive model can better describe its post-peak. Therefore, it is of great significance to strengthen the study of the residual stage of the rock after the peak and improve the damage structure model for the study of its mechanical properties.

2) Experimental aspect: the construction of the post-peak strain softening model of rock is too complicated, and it needs to be simplified and assumed. Generally, it is impossible to simulate the influence of rock softening on its stiffness degradation in indoor tests. Of course, there is also a lack of support from field construction measured data. As a result, the conclusions drawn from the test deviate from the actual situation, and the field measurement during the construction process plays an indispensable role in solving complex problems. However, there is little research in this area in the academic circle, so the use of on-site measured data for analysis and exploration is a major direction to make the research results more valuable in engineering applications.

3) Deformation control technology: The focus of research on the theory of strain softening support for roadway surrounding rock is on the support strength and the strength of the anchoring bearing structure, while ignoring the importance of anchoring as the structural stability of the bearing structure. At present, the coordination mechanism of the anchoring load-bearing law has not received extensive attention in engineering, and further research is needed in practice.

4) Softening in contact with water: There have been certain studies on the mechanism of rock softening in contact with water at home and abroad. However, the research on the structural model of rock softening and the interaction mechanism between water and structure in rock softening is relatively single, and it has not been studied on different scales. Therefore, it is the focus of future research to study the mechanism of water migration and internal structure changes on rock softening from a multi-scale perspective.

6. Conclusion
With the increasing demand for infrastructure construction all over the world, in the fields of energy extraction, hydropower development, and transportation, the development and utilization of underground space has become the main development trend of construction. With the depth of excavation of tunnels, tunnels, the strain softening of deep rock masses brings a series of thorny problems to mining and support. Therefore, in-depth study of the post-peak rock mass strain softening characteristics has important guiding significance for the design of safe and efficient deep rock mass
support excavation. This article summarizes a series of research results at home and abroad in recent years, points out the deficiencies and research prospects of existing research on this issue, and hopes to provide useful references for future related research.

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