Analysis of technical measures for controlling instability of surrounding rock in jointed rock masses

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Abstract. The development and utilization of underground space is an inevitable choice for the development of human society, economic construction, and national security strategy. The failure mechanism of the chamber in underground rock mass engineering is extremely complex, and its stability analysis and control have always been the key problems in the field of rock mechanics. In practical engineering, due to the complexity of the structural plane shape, unreasonable layout, increasing buried depth, and great disturbance of underground rock engineering, the stress concentration in the surrounding rock is intensified, the surrounding rock is extremely sensitive to the change of external load, and the stability state is prone to mutation, resulting in the instability and failure of the chamber structure. In this article, based on the previous theoretical research results and engineering practice experience, the instability control theory of surrounding rock of jointed rock masses on the bases of four basic principles of “consolidating surrounding rock joints, improving surrounding rock strength, restoring and improving stress state, and weakening dynamic disturbance source strength” was proposed. On this basis, to maintain the stability of the surrounding rock of the chamber, the chamber support form of “grouting reinforcement + full-face bolt (mesh) shotcrete combined support + local strengthening support + constructing impact buffer structure + reducing engineering blasting disturbance” was put forward. Moreover, the technical measures for controlling the instability of the surrounding rock of the chamber in jointed rock masses were established, and the technical scheme of joint application and step-by-step implementation was suggested. In addition, the principle of considering the safety and economy of support and the necessity of establishing a multi-parameter real-time joint monitoring and early warning system were discussed. The research results can provide a certain reference for the stability control of surrounding rock in jointed rock masses in similar projects.

1. Introduction
The development and utilization of underground space is an inevitable choice for the development of human society, economic construction, and national security strategy. However, the stability of surrounding rock in underground engineering is a complex nonlinear mechanical problem, which is...
usually accompanied by non-uniformity, discontinuous deformation, and large displacement [1]. To cope with the construction of various underground projects, foreign scholars began to focus on rock mass stability as early as the 18th century [2]. Especially at present, underground engineering worldwide continues to extend to the deep crust, and the frequency and intensity of engineering dynamic disasters such as rock bursts are remarkably increasing, and the complex mechanical characteristics of surrounding rock of deep caverns are quite prominent, which brings great challenges to the effective support of the caverns. However, due to the discontinuity, heterogeneity, anisotropy, and difference of occurrence conditions of the rock mass, it is difficult to accurately predict and evaluate cavern instability and failure.

To fundamentally solve the problems of support and stability control of surrounding rock of jointed rock masses and ensure the safe operation of underground engineering, it is necessary to study the deep stress field and occurrence conditions of the surrounding rock, gain insight into the deformation and fracture mechanism of surrounding rock, systematically put forward the theory of surrounding rock stability control of jointed rock masses, and form the supporting technology of surrounding rock support and stability control of jointed rock masses.

2. Instability control theory of surrounding rock in jointed rock masses

The stability of the surrounding rock of the jointed rock mass depends on the mechanical properties of the surrounding rock and the stress state [3]. The stress state includes static stress state and dynamic stress state caused by external load disturbance, both of which play an important role in the instability and failure of the surrounding rock. Therefore, improving the mechanical properties and stress state of the surrounding rock should be considered to control the stability of surrounding rock in jointed rock masses.

Surrounding rock mass is composed of intact rock and weak structural plane, and its mechanical properties are mainly controlled by the weak structural plane. Therefore, to maintain the stability of the chamber, according to the concept of active support, grouting reinforcement can be carried out in the area with relatively developed joints and fissures in the surrounding rock of the chamber. The mechanical properties of grouting materials should be close to or reach the mechanical properties of surrounding rock mass, and the grouting materials should be highly bonded with the surrounding rock mass to enhance the integrity of broken surrounding rock mass. For the development of groundwater around the cavern in the deep jointed rock mass, the high osmotic pressure drop will greatly increase the effective stress on the surrounding rock near the surface of the cavern. Especially in the areas of joint and fissure development, surrounding rock fracture, and fault zone, and the influence of high osmotic pressure drop is more obvious. Therefore, advanced grouting should be carried out in time to block and cut off the fissure water, so as to avoid the influence of large head pressure drop on the stability of the cavern after excavation.

Under the condition of high stress and strong impact disturbance, it is often impossible to obtain good supporting effects by adopting single grouting reinforcement measures. Therefore, based on the grouting reinforcement, it is necessary to change the mechanical properties of surrounding rock by installing supporting structures to enhance the bearing capacity of the surrounding rock. The deformation and failure of the surrounding rock of the jointed rock mass are generally characterized by shear slip along the joint plane and crack propagation along the joint tip, and its strength and deformation properties are mainly characterized by shear strength. Hence, the supporting structure should have the function of providing enough shear strength to improve the shear strength of the surrounding rock of the chamber and limit the shear deformation of rock blocks along the original joint plane and secondary structural plane, thus effectively enhancing the ability to resist shear failure of the surrounding rock of the chamber under the action of high ground stress and strong impact disturbance. In addition, the surrounding rock of the chamber also has strong brittleness, and it is easy to lose stability when small shear deformation occurs. Consequently, the supporting structure should not only have enough shear strength but also have enough deformation ability, so that the supporting
structure can effectively adapt to the deformation of cracks in the surrounding rock of the chamber, which can significantly improve the stability of the surrounding rock.

To ensure the stability of the chamber, in addition to improving the mechanical properties of the surrounding rock, it is also essential to improve the stress state of the surrounding rock. The excavation of the chamber breaks the original stress equilibrium state, and the stress redistributes, which leads to the stress concentration in the local position of the surrounding rock of the chamber [4]. After chamber excavation, the free face and surrounding rock near the surface of the chamber are usually in a two-dimensional stress state. Numerous studies show that the strength of surrounding rock in a three-dimensional stress state is greater than that in one-dimensional and two-dimensional stress state [5]. Therefore, the stress state should be restored and improved as soon as possible after the excavation of the cavern, and compressive stress should be applied to the free face of the cavern to restore the two-dimensional stress state of the free face and the surrounding rock near the surface to three-dimensional stress state, thus limiting the deformation of the surrounding rock along the normal direction of the free face and the joint plane. If the stress state of the surrounding rock can be effectively restored and improved in time and the compressive stress applied to the free face of the chamber is large enough, it will help to reduce the fracture expansion degree of the surrounding rock, improve the strength and self-bearing capacity of the surrounding rock, and reduce the deformation, thus maintaining the integrity and stability of the surrounding rock.

Additionally, when there is a dynamic load disturbance source near the cavern, the dynamic load propagates to the cavern space in the form of the elastic stress wave. When the stress wave is transmitted around the cavern, it interacts with the static load on the cavern, which may cause sudden changes in the stress state of the surrounding rock of the cavern and induce instability and failure. Under a certain buried depth, the development degree of cracks and joints in surrounding rock and the disturbance intensity of dynamic load on surrounding rock jointly determine the possibility, degree, and influence range of dynamic instability failure of the surrounding rock. For the dynamic disturbance source, the stronger the disturbance of dynamic load on the surrounding rock of the chamber, the more conducive to the sliding instability of rock blocks along the joint plane, the lower the induced critical static stress level of the surrounding rock, and the greater the failure range and degree of the surrounding rock. When the disturbance intensity of dynamic load to the surrounding rock of the chamber is low to a certain extent, it is difficult to induce instability and failure of the surrounding rock. Thus, after grouting and strengthening the joints and fissures in the surrounding rock, technical measures such as reducing the impact strength of the dynamic load source, weakening the propagation characteristics of the dynamic impact stress wave, and limiting the response behavior of the surrounding rock after disturbance can be taken to eliminate or weaken the disturbance strength of the dynamic load on the chamber and reduce the degree of instability and damage of the chamber or avoid instability and damage of the chamber, thus achieving the purpose of controlling the stability of the surrounding rock of the chamber. However, when the disturbance intensity of dynamic load is large and it is difficult to be effectively weakened, after determining the location of the dynamic disturbance source and the impact side of surrounding rock, the overall support strength especially the support strength of the impact side of the surrounding rock should be improved. The supporting structure under dynamic load disturbance is quite different from conventional support, which not only has the function of conventional support, must also possess the ability to effectively absorb disturbance energy and resist dynamic impact, which can improve the stability of surrounding rock.

Therefore, aiming at the stability and control of the surrounding rock of the jointed rock mass, the theory about the stability control of the jointed rock mass is proposed as follows:

1. Strengthen the joint and fissure development area of the surrounding rock of the cavern to improve the integrity of the surrounding rock of the jointed rock mass.
2. Adopting high-strength supporting structure can improve the shear strength of the surrounding rock of the jointed rock mass and limit the shear deformation of rock blocks along the original joint plane and secondary structural plane, and effectively enhance the ability to resist shear failure of the surrounding rock under the action of high stress and strong impact disturbance.
(3) After excavation, the stress state should be restored and improved as soon as possible, and enough compressive stress should be applied to the free face of the cavern to restore the two-dimensional stress state of the free face of the cavern and the surrounding rock near the surface to the three-dimensional stress state, which is favourable to improve the effective strength of the surrounding rock and limit the deformation of the surrounding rock along the normal direction of the free face of the cavern and the joint plane.

(4) When the surrounding rock of the cavern is disturbed by strong impact, priority should be given to eliminating or weakening the disturbance intensity of dynamic load to the cavern. However, when the disturbance intensity of dynamic load is large and difficult to be effectively weakened, the overall support strength of the surrounding rock of the cavern should be improved, and the support strength of the impact side of the cavern should be improved at the same time. The support system should have the ability to effectively absorb disturbance energy and resist dynamic impact.

According to the above control theory, in engineering practice, after determining the main factors (such as high stress, joint and fissure development, and strong impact disturbance) affecting the stability of the surrounding rock of the jointed rock mass, targeted technical measures are taken to maintain the stability of the surrounding rock. In concrete support, when two or more support and reinforcement measures need to be taken, the interaction and influence of various technical measures should be considered, and the safe and efficient construction of excavation and support of the chamber should be ensured as far as possible on the premise of realizing effective control of the stability of surrounding rock of the chamber.

3. Control measures for instability of surrounding rock in jointed rock masses
The above-mentioned theory of rock instability control of jointed rock masses needs to be realized by adopting corresponding technical measures. Because many factors affect the stability of the surrounding rock, it is necessary to comprehensively consider various influencing factors when controlling the instability of the surrounding rock. In the concrete implementation, the support method, selection of anchor types, and design of support parameters should be determined based on the geomechanical conditions of the project site (such as structural plane occurrence, surrounding rock quality grade, and stress state); moreover, the impact disturbance intensity and its influence on chamber stability should be fully considered to meet the support requirements for the stability of surrounding rock of the chamber. Given this, after a concise summary, the following technical measures are proposed to control the instability of surrounding rock in jointed rock masses.

3.1. Grouting reinforcement measures
The high-stress concentration and large deformation will appear in the joint development area of the surrounding rock under the action of external load, which seriously reduces the bearing capacity of the surrounding rock. This is an important factor leading to the instability and dynamic disaster of the chamber. The joints and fissures in the surrounding rock of the chamber are easy to cause the action range of the bolt or anchor cable to become smaller, and it is difficult to provide sufficient support force. Therefore, it is necessary to reinforce the joint development area in the surrounding rock by grouting, filling the slurry into the joint, so that the broken surrounding rock can be cemented as a whole again, improving the cohesion between the joint surface and the surrounding rock. High strength and high toughness grouting materials should be preferred for the surrounding rock with well-developed joints and fissures to fully consolidate and repair the fracture zone and damage zone in the surrounding rock, greatly improve the shear strength of the surrounding rock, so that the surrounding rock can effectively resist the disturbance of static and dynamic loads, and finally realize the long-term stability of the surrounding rock. Note that there are a large number of original joint planes in the surrounding rock, and new cracks will emerge after excavation or engineering disturbance. The expansion of new cracks needs a certain process, so it is important to choose the appropriate grouting time.
3.2. Full-face bolt (mesh) shotcrete combined support measures

Under the condition of high stress or strong engineering disturbance, it is difficult to achieve an ideal supporting effect using single grouting reinforcement, and the effective means is to carry out the full-face bolt-shotcrete combined support or bolt-mesh-shotcrete combined support (Figure 1). The combined support system can increase the stress area of the surrounding rock in the joint development area and make the stress of the supporting structure more uniform, which is helpful to improve the support capacity of the supporting structure to meet the requirements of the overall integrity of the cavern. For bolt or anchor cable supporting structure, the engineering practice shows that long bolt and large-diameter bolt have better-supporting effect on the surrounding rock of jointed rock masses. By increasing the length of the bolt, the long bolt can suspend the broken surrounding rock of the roof in the deep rock mass, anchor the surrounding rock with joint development to the deep surrounding rock area with good integrity, and slow down the deformation speed of the surrounding rock of the roof. Moreover, by applying a certain prestress, the surrounding rock with joint development can be squeezed and strengthened to maintain the stability of the cavern. For the same kind of bolt, the larger the diameter, the higher its strength, and the larger the radiation range of bolt prestress. When the bolt is installed perpendicular to the surrounding rock surface of the cavern, a relatively uniform compressive stress zone can be formed in the surrounding rock, which basically covers the anchoring zone and enhances the prestressed superposition effect of the bolt. In addition, to improve the stability of the cavern, it is possible to increase the tensile strength of supporting structures such as anchor bolts or anchor cables, reduce the distance between anchors or cables and increase the prestress, so that the effective compressive stress area formed by anchors in surrounding rock covers the whole joint development area, increasing the integrity and effective bearing range of supporting structure to form an organic whole, giving full play to the active supporting role of anchors, and better controlling the deformation and instability of surrounding rock.

![Bolt-shotcrete combined support](image1.png) ![Bolt-mesh-shotcrete combined support](image2.png)

**Figure 1.** Typical bolt-shotcrete and bolt-mesh-shotcrete combined support.

However, the support system and support technology under impact disturbance are quite different from the conventional static load support technology. In the anti-impact disturbance support, the supporting structure should not only withstand the high-stress load under static conditions, but also resist the dynamic load under impact disturbance (the supporting structure often reaches or exceeds the yield strength), and adapt to the instability and failure characteristics of the surrounding rock. Therefore, the supporting structure must not only have the function under static load but also have the ability to absorb disturbance energy and resist impact. At present, the supporting structures in most underground engineering are mainly anchors or cables. In many cases, the traditional anchors and cables are not ideal for resisting the impact disturbance of underground cavity (especially jointed chambers) during construction or service, but only alleviate the intensity of dynamic disasters to a certain extent, and fail to achieve the purpose of effective prevention and control of dynamic disasters. The fundamental reason is that some traditional anchors cannot effectively absorb the high deformation energy of surrounding rock and resist strong impact load, which is manifested in the fact that traditional anchors either have high stiffness and support strength, but small ductility and poor adaptive deformation ability; or can provide large deformation, but cannot meet the support strength.
under strong impact disturbance, which often leads to bolt fracture and failure due to excessive stress in surrounding rock, and it is difficult to meet the requirements of large deformation support of surrounding rock of deep jointed rock mass and prevention and control of strong impact dynamic disaster. Therefore, aiming at the instability and failure of the surrounding rock of the jointed cavern under impact disturbance, it is urgent to improve the traditional anchor rod and develop a new type of strong energy-absorbing and anti-seismic anchor (Figure 2), so that the anchor has multiple functions such as high strength, stable support, elastic restoration and high damping, which can not only absorb the deformation energy of surrounding rock greatly but also realize rapid yielding, that is, integrate energy-absorbing and anti-seismic functions, thus meeting the characteristics of surrounding rock failure of the underground jointed cavern. Especially when the surrounding rock of the chamber is subjected to impact disturbance, the anchor can control the safe release of impact energy while maintaining constant support resistance to achieve the purpose of suppressing the occurrence of impact power disasters or making the whole process of dynamic disasters safe and controllable.

![Figure 2. A new energy-absorbing and anti-seismic bolt [6].](image)

3.3. Local strengthening support measures
To realize the long-term stability of surrounding rock of jointed rock masses under the impact disturbance, the key is to monitor and strengthen the support of some key parts of the chamber under the premise of ensuring the integrity of the chamber to ensure the overall stability of the surrounding rock when subjected to large impact strength. Generally, the deformation of the side facing the impact is large and the damage is serious. In practical engineering, after the direction of the impact disturbance source is determined, the support strength at the impact side of the chamber should be strengthened, the bolt (mesh) shotcrete combined support mode should be adopted, the bolt support parameters should be optimized (such as reducing the bolt spacing, increasing the length, and diameter of the bolt) to improve the impact capacity of the joint development area and the impact side to reduce the impact intensity.

3.4. Construction of impact buffer structure
Under the condition of impact disturbance, after determining the impact tendency and potential dynamic disturbance source of the surrounding rock of the chamber, the impact buffer structure can be constructed in the surrounding rock with a certain distance from the chamber. The impact buffer structure can greatly attenuate the impact stress wave, absorb the impact energy, reduce the disturbance intensity of the impact stress wave to the surrounding rock of the chamber and weaken the damage degree of the surrounding rock.

3.5. Measures to reduce engineering blasting disturbance
Engineering construction disturbance has a significant influence on the stability of surrounding rock of jointed rock masses. To reduce the construction disturbance, that is, to weaken the strength of the dynamic disturbance source and reduce the amplitude of stress wave, it is necessary to design blasting parameters and construction methods reasonably, strictly control the charge quantity, and improve the charge structure and blasting method. For example, smooth blasting technology could be adopted to strive for no or less blasting cracks in the surrounding rock of the chamber after blasting to maintain the integrity of the surrounding rock to the maximum extent and improve the self-bearing capacity of
the surrounding rock. Meanwhile, the disturbance influence on other chambers nearby is small, which is conducive to maintaining the stability of the chambers.

The above-mentioned technical measures for controlling the instability of surrounding rock in jointed rock masses should be applied jointly according to the stability requirements of surrounding rock and implemented step by step, which is conducive to realize effective control of surrounding rock stability and construction safety in chambers. It should be noted that the factors affecting the stability of different projects and the corresponding deformation and failure characteristics are very different. Therefore, these measures should be combined with specific engineering characteristics when being implemented.

4. Discussion
In the support of the surrounding rock in the underground cavity, the pressure acting on the supporting structure is only a small part of the ground pressure, and the surrounding rock has a high self-bearing capacity, so the self-bearing capacity of the surrounding rock should be brought into full play. In addition, while improving the supporting effect of supporting structures, the engineering cost should be considered, and the appropriate supporting capacity and supporting needs should be compared. The required supporting structure type and its strength should be determined by calculating the safety factor or failure probability. The selection of supporting structure plays a very important role in its supporting effect, and it is necessary to follow the principle of adopting economy as much as possible on the premise of meeting the functionality and safety, which is beneficial to achieve both economical and effective supporting effect and ensure the safety of the chamber.

On the other hand, it is necessary to build a multi-parameter real-time joint monitoring and early warning system while taking control measures [7]. Because many factors are affecting the occurrence of surrounding rock disasters in jointed rock masses, it is difficult to achieve accurate monitoring and forecasting by using a single monitoring method. In-situ monitoring technologies such as displacement monitoring, acoustic emission, microseismic, electromagnetic radiation, and pressure can be jointly adopted to construct a multi-parameter real-time joint monitoring and early warning system for the surrounding rock of jointed rock masses in areas with strong engineering disturbance, to monitor micro-fracture signals and their positions in the surrounding rock online in real-time, record multi-source characteristic parameters in the process of surrounding rock fracture, and determine the multi-source precursor information characteristics of instability and failure of the surrounding rock. At the same time, accurately monitoring the deformation, stress distribution, and evolution of surrounding rock, and analyzing the local stress concentration of the surrounding rock can lay a foundation for early warning and control measures of instability and failure of the surrounding rock.

5. Conclusions
In this article, the instability control theory of surrounding rock of jointed rock masses based on four basic principles of “consolidating surrounding rock joints, improving surrounding rock strength, restoring and improving stress state, and weakening dynamic disturbance source strength” was proposed. On this basis, to maintain the stability of the surrounding rock of the chamber, the chamber support form of “grouting reinforcement + full-face bolt (mesh) shotcrete combined support + local strengthening support + constructing impact buffer structure + reducing engineering blasting disturbance” was put forward. Moreover, the technical measures for controlling the instability of the surrounding rock of the chamber in jointed rock masses were established, and the technical scheme of joint application and step-by-step implementation was suggested. The above-proposed theories and technical measures will be applied to engineering practice soon to verify their rationality and feasibility.

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