Triaxial unloading test of rocks and its implication for rock burst

R.Q. Huang, X.N. Wang, L.S. Chan

Abstract The behaviour of rock deformation and its failure characteristics under loading and unloading conditions are substantially different. In this paper, triaxial unloading tests have been designed to simulate the unloading process during tunnel excavation in three kinds of rock (granite, migmatitic granite and limestone). The results show that elastic moduli obtained under unloading conditions are generally less than under loading conditions. The strength of the rock samples also decreases with an increasing rate of unloading. This study reveals that rock bursts during tunnelling in a high in-situ stress area could be controlled or reduced by lowering the excavation speed or applying precautionary measures to control the displacement of surrounding rocks.

Résumé Les caractéristiques de déformation et de rupture des roches en condition de chargement ou de déchargement sont significativement différentes. Dans cet article, des essais triaxiaux de déchargement ont été conçus pour représenter le processus de déchargement qui accompagne le creusement d'un tunnel, dans trois types de roches (granite, granite migmatitique et calcaire). Les résultats montrent que les modules élastiques obtenus en condition de déchargement sont généralement plus faibles qu'en condition de chargement. Par ailleurs, la résistance des roches testées décroît lorsque la vitesse de déchargement augmente. Cette étude révèle que les phénomènes dynamiques de rupture brutale (rock bursts) pendant le creusement des tunnels dans des zones de fort état de contrainte initial pourraient être contrôlés ou réduits en diminuant la vitesse de creusement ou en mesurant et contrôlant les déplacements au voisinage de la zone en cours de creusement.

Keywords Triaxial test · Unloading · Rock burst · Granite

Mots clés Essai triaxial · Déchargement · Rock burst · Granite

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Introduction

Deformation and failure of rocks under unloading conditions are common in nature. Unloading due to rock slope cutting or tunnel excavation often necessitates stress adjustment in the rock mass near the free face and causes stresses to concentrate in some areas. Generally, a tunnel excavated in an area with a high horizontal stress is characterized by tensile stress on the tunnel walls and compressive stress on the roof of the tunnel (Goodman 1989). The unloading release may also provoke residual shear stresses in a rock mass and cause shear failure, which can be used to explain the disking phenomenon of boreholes in some high geostress regions (Wang and Huang 1990; Huang and Wang 1997). During the excavation of the foundation pit in the Gezhouba Dam on the Yangtze River (China), most of the slipping toward the free face occurred along weak, gently dipping surfaces (Wang et al. 1991).

Rock burst during excavation of tunnels in areas of high geostress is a typical failure phenomenon due to destressing. However, most rock mechanics experiments are designed for the loading condition, which may not be relevant to the study of the stress states of rock masses during excavation. Due to technical constraints and the complexity of excavation, the undertaking of experiments under unloading conditions is more difficult than under loading.

In this paper a triaxial test was made to simulate the process of rock burst due to unloading. Samples of granite and migmatitic granite from the Qinling Tunnel of Xi'an-Ankang Line and a limestone from Panzhihua were selected to analyse the deformation and failure characteristics of rock under two different unloading conditions. The results of the experiment and their implications on rock burst are discussed.

Experiment design of the triaxial unloading test

The state of stress around an underground tunnel modifies progressively during excavation. In general, the magnitude of radial stress decreases gradually toward the free face of the tunnel and reaches zero on the tunnel wall. The variation of the tangential stress is more complex. In some cases, the tangential stress increases gradually toward the free face and attains a maximum on the tunnel wall – a situation known as compressive stress concentration. In other cases this is reversed and the stress may become tensile in nature on the tunnel wall – a situation known as tensile stress concentration – where again it reaches its maximum.

Suppose the radial stress (σ_r) and the tangential stress are, respectively, the minimum and maximum stresses at a point in the surrounding rock of a tunnel. During a tunnel excavation, σ_3 (the minimum stress) always decreases while the maximum stress (σ_1) may decrease, increase or remain constant. In all cases, the stress difference ($\sigma_1-\sigma_3$) may reach the critical state and failure occurs, causing rock bursts on the tunnel wall. In order to simulate such a process a triaxial experiment was designed in which σ_3 was progressively decreased to simulate the unloading process.

A granite and a migmatitic granite from the Qinling Tunnel and a limestone from Panzhihua were selected for the experiments. The former two samples were collected from a location where rock bursts had occurred. Standard test samples with a length of 120 mm and a diameter of 50 mm were prepared. The experiments were carried out using the Material Testing System (MTS815) at the National Laboratory of Geological Hazard Prevention in Chengdu University of Technology. It uses a servo-control machine with a digital Teststar unit. Two unloading control modes, displacement control (LVDT) and load control (FORCE) were used in the tests.

In the LVDT mode, the rock sample was first kept at hydrostatic pressure. The axial stress was then increased incrementally while the axial displacement rate was kept at a constant. The confining pressure was then reduced gradually until the sample failed. The typical stress path of this mode is shown in Fig. 1, in which point *S* represents the hydrostatic pressure state, *SU* the loading process, *UF* the unloading process and F the failure point.

The force control mode (FORCE) is similar to that of the displacement control mode, except that the force increment rather than the displacement is kept at a constant rate. The typical stress path of this mode is shown in Fig. 2, in which point S' is the hydrostatic pressure state, S' U' represents the loading process, point U' the start of the unloading stage, U' F' the unloading process and point F' the failure point.

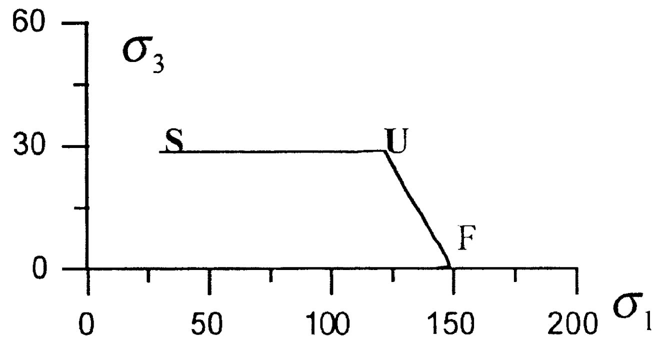

Fig. 1
Stress path of LVDT control type under unloading conditions

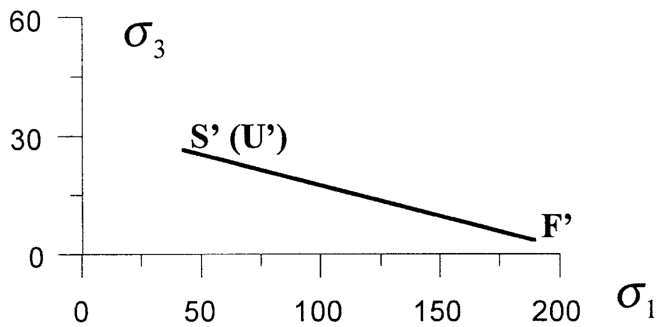

Fig. 2
Stress path of FORCE control type for unloading process test

Essentially, the most important difference between these two modes is that the ratios of the decrease in the confining pressure ($\delta\sigma_3$) to the increment of axial stress ($\delta\sigma_1$) during the unloading process are different. The unloading ratio ($\Delta\sigma_3/\Delta\sigma_1$) was 1.13 for the LVDT mode and only 0.14 for the FORCE mode. The unloading ratio in the unloading process controlled by LVDT was higher than that in the unloading process controlled by FORCE.

Deformation and failure behaviour of rocks under unloading conditions

As shown in Figs. 3, 4 and 5, the deformation characteristics under loading conditions are significantly different from those under unloading conditions. The angles of the stress-strain lines in the loading condition are generally higher than those in the unloading condition, i.e. the elastic modulus in the loading stage is higher than that in the unloading stage.

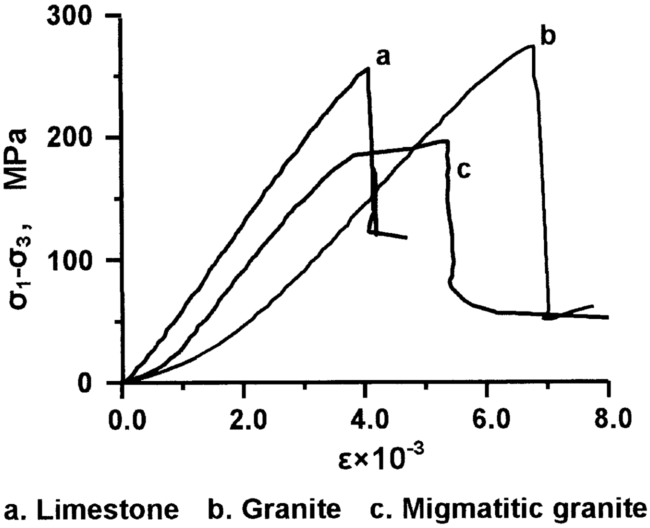

Fig. 3
Stress-strain curve of rocks under loading conditions

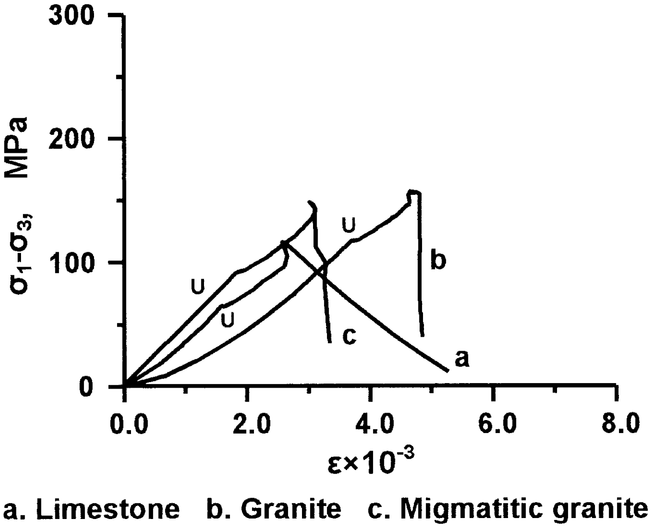

Fig. 4
Stress-strain curve of rocks under unloading conditions controlled by LVDT

For a comparison, the rock specimens were first tested during loading conditions and subsequently under unloading conditions using either the LVDT or FORCE mode. The results for the loading tests are shown in Fig. 3 and for the unloading conditions in Figs. 4 and 5 respectively (see also Table 1). For the Panzhihua limestone, the modulus in the loading stage is 67 GPa and that in the unloading stage, 36 to 46 GPa. For the migmatitic granite in Qinling Tunnel, the elastic modulus under loading conditions is 53 GPa and under unloading conditions, 44 GPa. The strength of the rock under unloading conditions is lower. The stress difference at the failure point under unloading conditions controlled by LVDT is also significantly lower than that under loading conditions. For

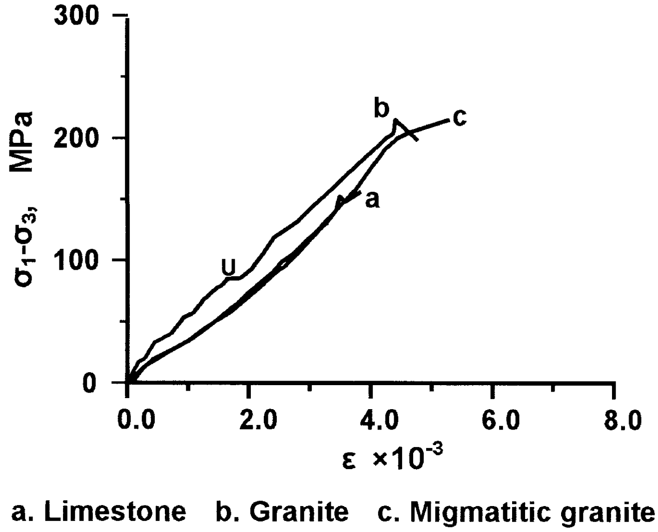

Fig. 5
Stress-strain curves of rocks under unloading conditions controlled by FORCE

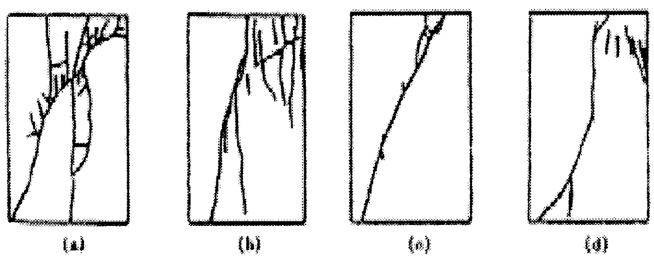

Fig. 6a–d
Failure patterns of rocks under unloading conditions. **a** Limestone in Panzhihua, unloading, controlled by LVDT, tensile failure ($\sigma_1=118.0$ MPa, $\sigma_3=2.4$ MPa). **b** Migmatitic granite in Qinling Tunnel, unloading, controlled by LVDT, shear-tensile failure ($\sigma_1=161.0$ MPa, $\sigma_3=5.4$ MPa). **c** Limestone in Panzhihua, unloading, controlled by FORCE, shear failure ($\sigma_1=226.6$ MPa, $\sigma_3=12.3$ MPa). **d** Migmatitic granite in Qinling Tunnel, unloading, controlled by FORCE, tensile shear failure ($\sigma_1=215.0$ MPa, $\sigma_3=0.6$ MPa)

the limestone in Panzhihua, the strength under loading conditions was 273 MPa, compared to 155 MPa under unloading conditions.

The tests show that under loading conditions and a low confining pressure, the rock failed by shear and the rupture angle β (angle between the failure plane and the maximum principal stress) was relatively large. For the same confining pressure in unloading conditions, a composite shear-tensile failure mode was observed and the rupture angle β decreased with axial stress.

The failure patterns of rock samples under unloading conditions are shown in Fig. 6 where (a) and (b) are the failure patterns in the LVDT mode and (c) and (d) are the failure patterns in the FORCE mode. It is of note that under unloading conditions the dominant failure mode of the rock was tensile or composite tensile-shear if the

Table 1
Results of behaviour of rock under loading and unloading conditions

Rock type	Controlled mode	Stresses before unloading		Deformation stresses and failure characteristics					Elastic modulus	
		Axial stress (MPa)	Confining pressure (MPa)	Axial stress (MPa)	Confining pressure (MPa)	Stress difference, $\sigma_1-\sigma_3$	Rupture angle, β (°)	Failure mode	Loading condition (GPa)	Unloading condition (GPa)
Panzhihua limestone	Loading	–	–	261.54	10	251.34	18	Shear	67.05	–
	Unloading with LVDT control	38.97	30	118.05	2.43	115.62	6	Tensile	–	36.18
	Unloading with FORCE control	38.97	30	226.66	12.26	214.40	20	Shear	–	46.05
	Unloading with FORCE control	30.53	30	165.41	9.97	155.44	15	Shear	–	44.82
Qinling granite	Loading	–	–	283.37	10	273.87	19	Shear	53.48	–
	Unloading with LVDT control	45.47	30	160.98	5.41	155.57	14	Shear-tensile	–	40.73
	Unloading with FORCE control	30.53	30	214.93	0.63	214.80	6	Shear-tensile		44.88
Qinling migmatitic granite	Loading	–	–	206.70	10	196.70	19	Shear	51.13	–
	Unloading with LVDT control	42.22	30	148.24	0.76	147.48	11	Tensile-shear		42.59

confining pressure was low, whereas with higher confining pressure it was shear.

Discussion

The tests reported in this paper reveal that rocks have lower elastic moduli under unloading conditions than under loading conditions. Moreover, the moduli decrease with an increased rate of unloading. As a consequence, it is difficult to understand or predict the occurrence of rock bursts when testing rocks under loading conditions and hence in areas of high geostress.

Theoretically, the decreasing moduli of rocks would imply that the rocks would be more deformable in their in situ state. In the triaxial test, the deformability of a rock sample depends on the micro-fracture mechanism of the rock prior to reaching peak strength and the total failure. As shown in Fig. 6, the rupture patterns of rocks under unloading conditions are generally tensile or tensile-shear. As a consequence, prior to the main observable fracture, lateral dilation may occur due to tensile micro-fractures in a sample, such that the sample becomes more deformable and a lower modulus is recorded. Obviously, the higher the unloading speed, the more intense will be the dilation in the sample and the lower the modulus.

Table 1 also indicates that the higher the unloading ratio, the lower the strength. The unloading ratio between the decrease in confining pressure and the increment of axial stress ($\Delta\sigma_3/\Delta\sigma_1$) in the unloading process in the LVDT mode was 1.13 and that in the unloading ratio in the FORCE mode 0.14. The rock strength under unloading conditions in the LVDT mode was lower than that in the FORCE mode. For the Panzhihua limestone, the stress difference at the failure point under unloading conditions controlled by LVDT is 115 MPa (corresponding confining pressure is 2 MPa), while when controlled by FORCE it is 214 MPa (corresponding surrounding pressure is 10 MPa). For the migmatitic granite in Qinling Tunnel, the stress difference at failure under unloading conditions controlled by LVDT is 155 MPa (corresponding confining pressure is 5 MPa), while that under unloading conditions controlled by FORCE is 214 MPa (corresponding confining pressure is 0.6 MPa). From the above, it is likely that the excavation speed in areas of high geostress could be an efficient way to control rock burst, while the use of NATM may help control and limit the displacement of the host rocks.

In the unloading process during a tunnel excavation, the lateral pressure in the surrounding rock is released. The inherent stresses readjust, but failure of rock may occur if the adjusted stress state becomes overly critical. Here it would be anticipated that the mode of failure would be tensile or composite shear-tensile. In areas where the in situ rocks are highly stressed, quick unloading due to tunnel excavation would result in a series of discontinuous tensile cracks parallel to the tunnel walls and the development of a "slaty" structure in the surrounding rock. Tan (1989) used the scanning electron microscope (SEM) to analyse some rupture planes of rock bursts which occurred in the Tianshengqiao hydropower station. He found that the rupture planes were of the tensile or tensile-shear type, which supports the results of the experiments under unloading conditions. When this kind of "slaty rupture" develops further and propagates toward the interior, rock bursts will occur.

Conclusions

The deformation and failure characteristics of rocks under unloading conditions and their significance for rock bursts have been studied. Based on the experimental results, the following conclusions can be drawn:

1. The deformation and failure characteristics of rock under unloading conditions are different from those under loading conditions. Under unloading conditions, the elastic modulus obtained is smaller than that under loading conditions and the ultimate strength decreases with the increase in unloading rate.
2. Rock bursts could be controlled or released by adjusting the speed of excavation, that is lowering the excavation speed in highly stressed areas, or taking some measures, such as NATM excavation techniques, to control the release of the displacement of surrounding rocks.
3. Rock bursts occur in the unloading process of tunnel excavation and their characteristics are closely related to the deformation and failure characteristics of the rock. Most rock bursts involve tensile or composite tensile-shear composite failure. This is the main reason why rocks have a lower modulus under unloading conditions.

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