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Unload Pull-out Test of Full-length Grouted Bolts in Slope Reconstruction and Expansion

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Highlights:

- The Unloading Pull-out Test Method (UPTM) is proposed to test the work load and ultimate load of bolts.
- 21 pull-out destructive tests were applied on site.
- Existing bolt stress loss in highway slope after 20 years.

Abstract. The Unloading Pull-out Test Method (UPTM) is proposed to evaluate the residual stress of existing anchorage systems and explore the actual stable state of the slope before excavation. A series of destructive pull-out tests are applied to detect the working state of the existing rock bolts. The working load and ultimate load of the existing bolts are determined by field test measurement of the P-S curve. The experimental result showed that a displacement increment of the bolts was present in the elastic stage, the elastoplastic stage, the slip stage, and the debonding stage. The working load and the ultimate load were in the elastoplastic stage and the debonding stage respectively. The working load of the bolts is closely related to the sliding deformation. The ultimate load of the bolts, however, is only related to the design parameters, slope lithology and other factors. After 20 years of natural forces acting on the bolts in the slope, their ultimate bearing capacity had a stress loss of 24.0% ~ 32.0%.

Keywords: *grouted bolt; load mechanism; pull-out test; rock slope; work load.*

1 Introduction

In recent years, the widening of Chinese highways has gradually increased, which has caused a large number of secondary excavation projects on existing high-slope highways [1,2]. The working conditions of bolts used as support measures for high slopes are a key issue in the study of secondary excavation stability [3]. Since traffic continues using the highways during high-slope excavation, the safety of passing vehicles is related to the stability of the slope.

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Non-destructive testing and destructive (pull-out) tests are the major detection methods to measure working conditions. Non-destructive bolt testing technology stimulates the stress wave or sound wave at the end of the bolt, where the end probe receives the reflected wave and infers the working state of the bolt [4,5]. Pull-out testing uses the load corresponding to the curve inflection point or the corresponding load as the working load of the bolt [6]. Ito [7] used an X-ray CT scanner to monitor the failure process in a pull-out test model and analyzed the microscopic damage to the anchor body in a laboratory pull-out test. The pull-out test show that the effective anchor length of a rock bolt is only 1.5 ~ 2.0 m, while the effective anchored length of a soil anchor can reach 10.0 m [8]. Research has shown that under pull load, the bolt first produces sliding failure at the bolt end [9]. Based on the shear displacement method, axial force and shear stress formula have been derived during the pulling process of the full-length grouted anchor. There is a sudden change in the anchor shear stress and the anchor axial force at the interface of the stratum, and the degree of mutation is closely related to the physical and mechanical properties of the stratum [10]. You [11] used the inflection point method to consider the influence of the elongation of a cable under a pulling load and the elongation of a cable under the rebound of rock and soil.

Research on the load transfer mechanism of bolts is an important means of revealing their macroscopic bearing capacity. An effective calculation method was developed for measuring the bond strength in a pre-stressed bolt between the grouting body and rock [12]. Others have studied the influence of the interfacial bond strength between grouting material on the surface and the relative stiffness of rock mass properties, grouting material properties, and beam materials on the anchoring force transmission and destruction mechanism [13-17]. Duan [18] and Guo, *et al.* [19] derived the differential transfer equation of the mechanics of a rock bolt and gave the failure type and the theoretical solution of the ultimate load of rock bolts.

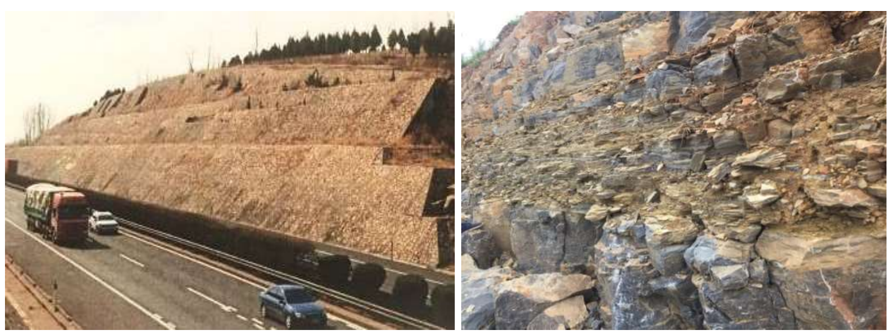
Zhang, *et al.* [20] used the interface shear stress redistribution hypothesis to define the interface shear stiffness softening curve and studied the typical component drawing test process. Approximately 80 laboratory rock bolt pull-out tests were carried out to study the effect of grout properties and bar shape on the ultimate bolt load capacity [21,22]. A series of 50 bolts were tested to determine the anchorage strength in hard-rock field conditions by conducting pull-out tests at different durations in [23].

The main purpose of the pull-out test is to study the quality of a bolt after the construction of a slope. The influence of the bolt-grout interface bond strength on peak load and failure can be studied using the distinct element method (DEM) [24-26]. However, few studies have been done on the load mechanism of bolts by on-site pull-out destructive tests. The current study investigated the secondary excavation of a high rock slope. The UPTM is proposed to test the working load and ultimate load of a full-length grouted bolt, and the working state of the bolt was evaluated.

2 Pull-out Test

2.1 Test Conditions

There are many high rock slopes involved in the reconstruction and expansion project of the Beijing-Shanghai Expressway. Due to the influence of its reconstruction and expansion, it is necessary to carry out secondary excavation of some high slopes along the road. The cutting slope K593+260 ～ K593+555 is located in Yinan County, Linyi City. The jointed rock slope height is 32.0 m. Since the opening of the Beijing-Shanghai Expressway in 1999, the K593+260 ～ K593+555 cutting slope has exhibited multiple deformation and instability trends. The status of the existing slope and the relative geographical relationship with the road are shown in Figure 1. After supplementing with Φ32 full-length cemented anchor support measures it was eventually stabilized; the existing slope support forms are shown in Figure 2. However, excavation of the slope requires the removal of the existing anchor bolts, which will affect the stability of the slope.



a b

Figure 1 K593+260 ~ K593+555 slope: (a) the relative geographical relationship between slope and highway, (b) rock joints in K593+260 ~ K593+555 slope.

In order to evaluate the stability of existing slopes, the stress state of bolts in the slopes was analyzed. The working load and ultimate load of existing support bolts measured by pull-out tests and the design parameters of the existing anchors are shown in Table 1.

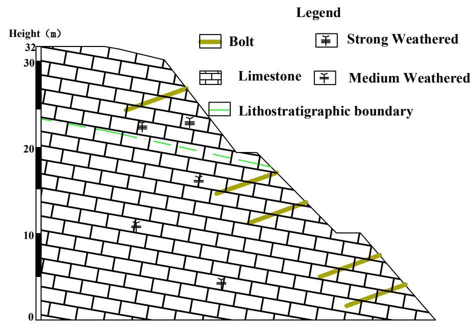


Figure 2 Existing slope support forms.

Table 1 Bolt design parameters.

Rock bolt	Design parameters
Length	8 m
Diameter	Φ32
Incidence	20°
Inter-row spacion	Row spacing 4 m, horizontal spacing 3 m,
Strength of rock bolt	HRB400
Design load	250 kN

As the K593+260 ～ K593+555 slope features full-length grouted bolt support, the rock-bolt heads are sealed in a masonry wall. Because the bolt heads are completely sealed, it is difficult to perform a bolt load test directly. In response to this problem, the Unloading Pulling-out Test Method is proposed. The bolt is unloaded in the shallow layer of the slope and then a pulling load is applied to the bolt and the load-displacement (P-S) curve is recorded. Exposed bolts where the slope has been excavated were selected as test positions, as shown in Figure 3.

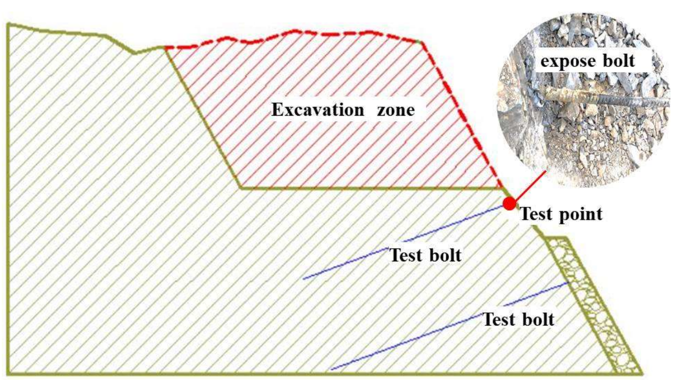


Figure 3 Bolt detection point position.

2.2 Test Design

Pull-out test points were selected on second- and third-grade slopes of K593+260 ～K593+555. A series of pull-out tests were applied at the third-grade and second-grade slopes. There were 5 upper row bolts and 7 lower row bolts in the third-grade slope, and 9 in the second-grade slope. The bolt pull-out test positions are shown in Figure 4. The bolt design parameters and the rock parameters of the reinforcement positions are shown in Table 2.

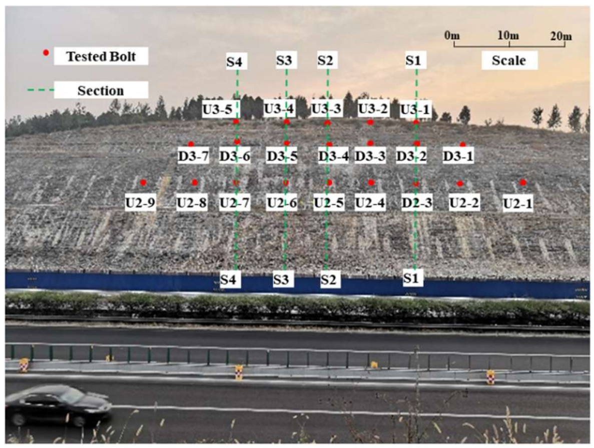


Figure 4 Layout diagram of the 21 tested bolts in the K593+260 ～ K593+555 slope.

Table 2 Strata and lithology at the anchorage points of the tested bolts.

Bolt position	**Strata and lithology**	**Rock mass parameters**
Third grade slope upper row (U3)	Moderately weathered limestone strata	c = 24 kPa, φ = 49°
Three grade slope down row (D3)		
Second grade slope upper row (U2)	Weathered limestone + marl	c = 26 kPa, φ = 55°

2.3 Method

2.3.1 Test Devices

The test instrument consisted of a ZP-100T manual hydraulic jack combined with an anchor and displacement gauge to complete the test system. The working mechanism is that the hollow jack applies a top thrust to the anchor and the anchor transforms the top thrust into a tensile force applied to the bolt. The load-displacement curve is recorded during the whole test procedure, the load is applied stepwise. The test system is shown in Figure 5.

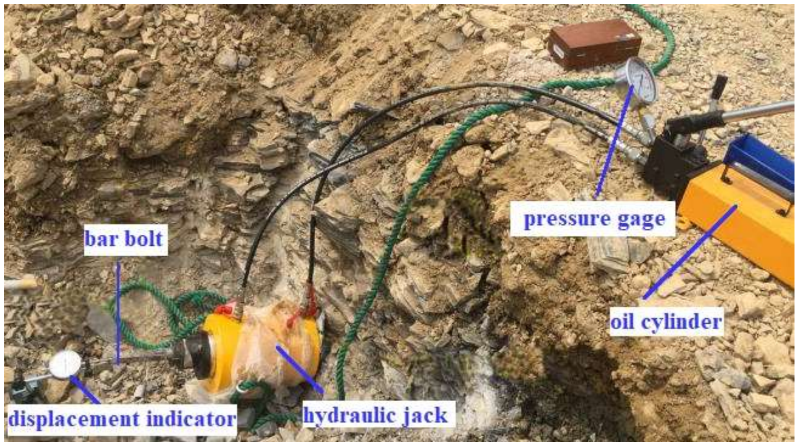
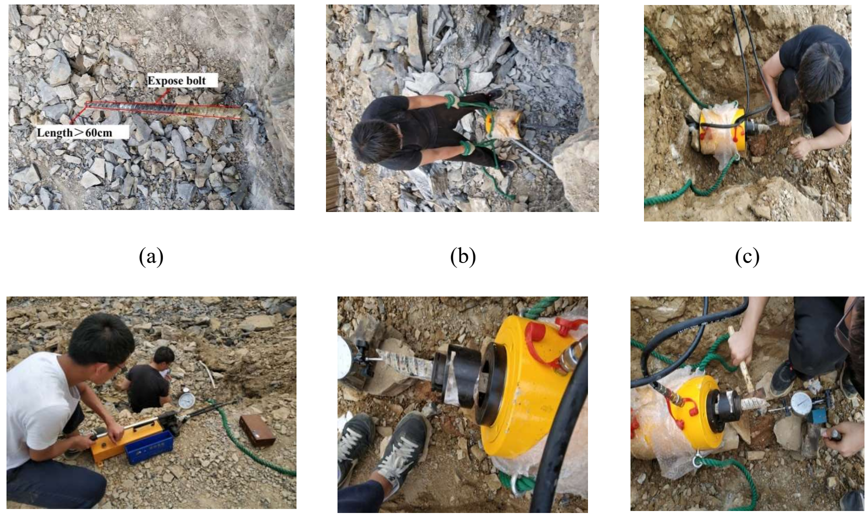


Figure 5 Bolt pull-out test device on site.

2.3.2 Test Procedure

Three sections were selected to detect the working load of the bolts. The pull-out test is carried out in the following 6 steps (see Figure 6):

1. Surrounding rock is excavated at the test point so that the exposed length of the tested bolt is at least 60 cm.
2. Oil quantity, exhaust, indication of the pump cylinder and tension meter are checked to ensure that the hydraulic system is connected when the oil reservoir is full.
3. The exposed bolt is put on the hydraulic cylinder so that the piston ends face outward and the joint length and the matching bolt tension gauge adapter are connected; then the nut and the drain valve are tightened clockwise.
4. In order to ensure a tight fit between the pad and bolt, 20 kN is pre-applied to the bolt. Later, the load is increased in increments of 10 kN to 200 kN .
5. The displacement is read immediately after the application of each load until the load is stable, continued by recording the displacement at the first minute, and the load-displacement curve under each load is drawn.
6. When the load-displacement curve shows a displacement point or a mutation zone, the pressurization is stopped.



(a) (b) (c)

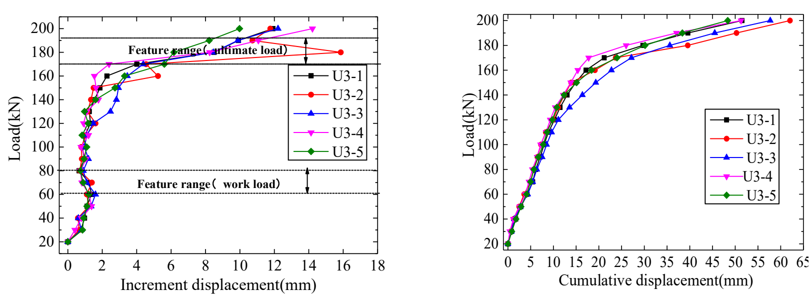
(d) (e) (f)

Figure 6 Unloading Pull-out Test Method procedure.

3 Results and Discussion

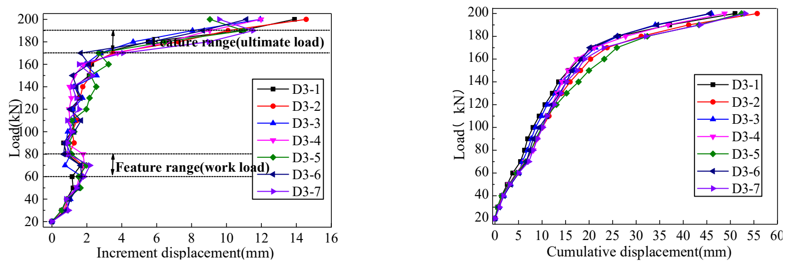
3.1 Behavior of Grouted Bolts Under Pull-out Test

The load-increment displacement and cumulative displacement of the 21 tested bolts under various loads are shown in Figures 7- 9.



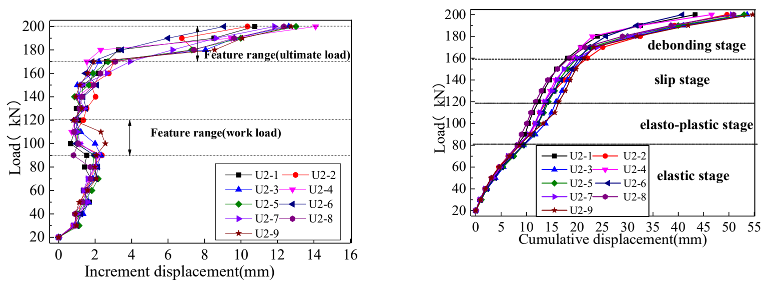
(a) (b)

Figure 7 P-S curve in grade Ⅲ slope (U3): (a) bolt increment displacement with different tensile forces; (b) bolt cumulative displacement with different tensile forces.



(c) (d)

Figure 8 P-S curve in grade Ⅲ slope (D3): (a) bolt increment displacement; (b) bolt cumulative displacement.



(a) (b)

Figure 9 P-S curve in grade Ⅱ slope (U2): (a) bolt increment displacement; (b) bolt cumulative displacement.

It can be seen from Figures 7-9 that the displacement of the bolts in both slope grades under the pulling load had a nonlinear trend. When the pulling load was increased step by step in the range of 20 ~ 60 kN, the displacement increment and cumulative displacement increased gradually. This is the elastic deformation stage, mainly due to the deformation of the bolt. The displacement increment suddenly decreased at a load of around 60 kN ~ 80 kN. In the elastoplastic deformation stage, the bonding force between the grouting body and the bolt begins to restrict the bolt displacement. Meanwhile, when the pulling load was increased from 80 kN to 160 kN, the displacement increment increased gradually and the load-displacement curve increased slowly. This is the slip stage, in which most of the deformation produced is the deformation of the grouting body. Finally, when the pulling load exceeded 160 kN, the load-displacement curve increased significantly. When the pulling load was increased to 200 kN, the displacement increment under single-stage load was about 10 mm. At this time, the bolt and the surrounding grouting body enter a state of failure, which is the debonding stage.

3.2 Unloading and Pull-out Mechanism Analysis

The two peak point phenomena of the bolt displacement increment were observed under unit load. When the pulling load was applied again at a certain load level, the displacement increment decreased and the cumulative displacement increased. In combination with the actual conditions during the test, excavation was continued until 0.6 m into the slope and the bolts were subjected to a drawing test in the unloaded initial state. The analysis of the bolt loading mechanism during the pull-out test is shown in Figure 10.

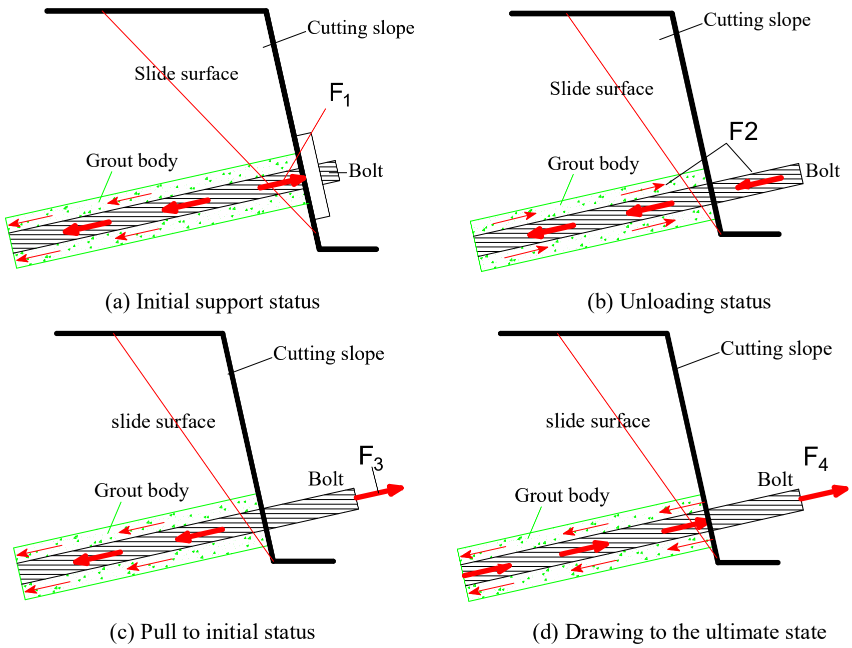


Figure 10 Bolt pull-out mechanism: (a) initial support status; (b) unloading status; (c) pull to initial status; (d) drawing to the ultimate state.

As shown in Figure 10(a), in the working state creeping deformation is produced in the slope along the potential slip surface. The rock mass applies shear deformation to the bolts and the anchor pad, causing the bolts to undergo outward tensile deformation. Meanwhile, the deep and stable rock mass has a restraining effect on the outward displacement of the grouting body and the bolts. Under the action of the deformation constraints of the sliding rock mass and the stable rock, tensile load F1 is generated in the bolts and the slope is in a stable state under the support of the bolts. Bolts that have been in a tension state for a long time experience a certain degree of elongation deformation, coupled with creep of the rock mass and the bolt.

As shown in Figure 10(c), when the pulling load increases, the anchor gradually returns to the working state of stress. When the displacement generated by the pulling reaches the retraction amount generated by the unloading, pulling force F3 applied to the anchor can be regarded as the equivalent of the work load of an existing bolt. When the pulling load exceeds F3, new slip deformation occurs between the bolt and the surrounding rock. It starts from the outermost end of the anchor and gradually expands inward. When the pull load is low, at the first pulling load level both the displacement increment and the cumulative displacement increase. The pulling load reached even exceeds the first pulling load, and the cumulative displacement increases slowly.

As shown in Figure 10(d), when the pulling load reaches a certain level, the bolt is subjected shear deformation from the rock mass. Tension F4 is provided by the puller and the friction. The bolt enters the state of failure while the anchor system enters the yield state; continued loading will cause damage. Corresponding to the load-displacement curve, the displacement increment under each load is over 10 mm and shows a significant break. The pulling force F4 can be seen as the ultimate bearing capacity of the bolt.

3.3 Work Load and Ultimate Load

According to the proposed method, the working load of existing bolts was obtained in the range from 60 kN to 100 kN, while the ultimate bearing capacity was in the range of 170 ~ 190kN. In order to analyze the slope stability of different positions, 4 sections were selected in the slope. The bolt working load and ultimate bearing capacity in sections 1 to 4 in Figure 4 are plotted in Figure 11, where U3 is in the upper row in the grade III slope; D3 is in the lower row in the grade III slope; U2 is in the lower row in the grade II slope.

As can be seen from Figure 11, there was no significant difference in the load of the bolts between sections 1 and 4. It shows that the working load of the bolts was greater in U2. The ultimate load of the bolts in each section was almost the same in different positions. The working load of the row anchors on the secondary slopes in the four sections was 90 kN, which is a very significant numerical increase compared to the 60 kN of the upper row of anchors on the tertiary slope. The working load of the bolts is caused by the residual sliding force of the unstable rock mass. It can be seen that the second-grade slope of the slope had a stronger sliding deformation trend than the third-grade slope, which may be caused by a sliding surface on the second-grade slope. The ultimate loads of the bolts at different positions were almost the same; all were in the range from 170 kN to 190 kN. This shows that the ultimate load of the bolts is independent of the sliding deformation trend of the slope and is only related to the bolt design parameters and the lithology of the slope rock mass.

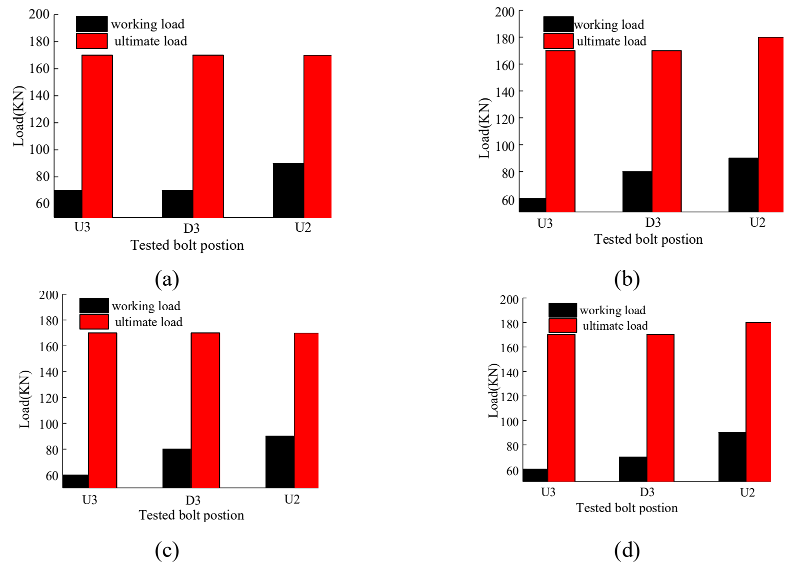


Figure 11 P-S curves in different sections: (a) section 1; (b) section 2; (c) section 3; (d) section 4.

4 Conclusions

Whether the safety of the slope can be guaranteed after over 20 years of long-term external forces remains to be verified by the project. Based on the reconstruction and expansion project of the Beijing-Shanghai Expressway, this paper analyzed the working load and ultimate load of existing bolts using an on-site pull-out destructive test to verify the stress loss of the anchors under long-term action. The results showed that the stress loss of the bolts was 24.0 ~ 32.0%. The UPTM was proposed to detect the working state of the bolts. The main conclusions that can be drawn are as follows:

1. The 21 pull-out tests showed that the trend of the load-displacement (P-S) curves was the same for all bolts, going through an elastic stage, an elasto-plastic stage, a slip stage, and a debonding stage. Among them, the loads corresponding to the elastoplastic stage and the debonding stage are the working load and the ultimate load respectively.
2. When the pull load was small, the bolts exhibited elastic deformation. While the pull-out load increased, the bolts and the grouting body exhibited

simultaneous deformation. The bolt and the grouting body exhibited slip deformation until the displacement increment of bolt head was over 10 mm.

3. The working load of the bolts in a jointed rock slope outside is closely related to the sliding deformation trend of the slope. The strongest sliding deformation trend of the rock mass is near the middle of the slope.
4. The ultimate load of the bolts is independent of the sliding deformation trend of the slope. It is only related to the bolt design parameters and the lithology of the slope rock mass.
5. The displacement of the anchoring system under the pulling load can be attributed to the deformation of the grouting body. When the deformation of bolt head reaches the limit of the grouting body, the bolt anchoring system enters the yield-destruction stage. After having been subjected to natural forces for 20 years, the bolts showed a significant stress loss. The ultimate bearing capacity stress loss of the bolts was 24.0% ~ 32.0%.

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