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TECHNICAL NOTE

Failure Mechanism of Unbonded Prestressed Thru-Anchor Cables: In Situ Investigation in Large Underground Caverns

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1 Introduction

Prestressed rock anchor cables are commonly utilized in geotechnical and mining engineering (Peliua et al. 2000; Tezuka and Seoka 2003; Koca et al. 2011) because their installation increases the effective strength and stability of the reinforced rock (Maejima et al. 2003; Li et al. 2012). Nevertheless, in some cases, prestressed cables have failed in large underground caverns or tunnels because of excessive deformation of the anchored rock mass or inadequate assumptions used when designing the cables (Li 2004; Lu et al. 2011; Gong et al. 2011). During the failure process of anchor cable, the stress redistribution and progressive deterioration of the reinforced mass rock can adversely affect the overall stability of the free surface, manifested as large deformation or indeed collapse of rock mass (Galvez et al. 2006; Zhu et al. 2010). Therefore, a deeper understanding of the mode and mechanism of prestressed anchor cable failure will better inform the design process of anchor cables to mitigate future failures.

Prestressed anchor cables can be categorized into three general groups based on the anchoring method (Jarred and Haberfield 1997; Chen and Yang 2004): (1) tip-grouted anchor cables that have grout-bonding segments and free segments; (2) fully grouted anchor cables with anchor wires that are fully bonded with the rock; (3) prestressed thru-anchor cables that have two anchor bases without grout-bonding segments. The tip-grouted and fully grouted prestressed cables have been the subject of research more than the thru-anchor cables because they have more extensive applications (Spang and Egger 1990; Hyett et al. 1995; Serrano and Olalla 1999; Huang et al. 2002; Cai et al. 2004; Ugur et al. 2011). Even less attention has been paid to the unbonded prestressed thru-anchor cables (UPTACs) based on the limited information available in the academic and professional literature. The mechanical interactions of UPTACs are different from those of grout-bonding cables because the UPTAC does not have a grout-bonding section, but has two anchor bases. Under loading, the prestressed cable can restrain the deformations of the anchored rock, and the anchored rock can also transfer the rock stress to the cable via the bridge of anchor bases.

This paper focuses on evaluating the failure mechanism of UPTACs based on a case study of underground caverns in Sichuan Province, China. Several external failure modes of the UPTACs observed in this project are first presented and special design techniques for the UPTACs in the large underground caverns are summarized based on in situ investigation: failure depth of disabled UPTACs, break face, measured working load and installation method.

2 Overview of UPTACs in the Jinping II Underground Caverns

2.1 Background

The Jinping II hydropower station, the largest powerhouse in the Yalong River valley, is located in Liangshan County, Sichuan Province, China (Jiang et al. 2010, Feng and

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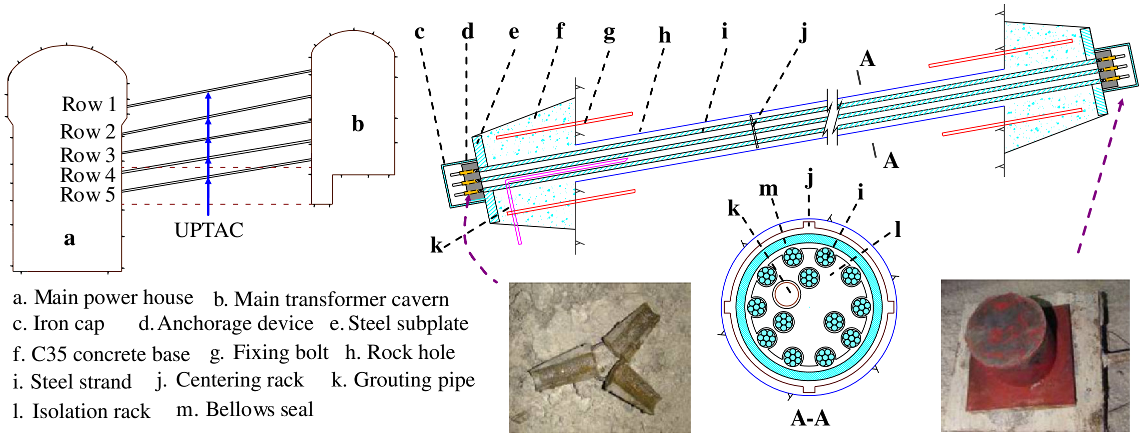

Fig. 1 Designed UPTAC for the pillar between the main powerhouse and the main transformer cavern

Hudson 2011). Its underground main powerhouse is 352.4 m long, 28.3 m wide and 72.2 m high. The main underground transformer cavern, which is parallel to the main powerhouse, is 374.6 m long, 19.8 m wide and 34.1 m high. The marble pillar between the main powerhouse and the main transformer cavern is approximately 45 m thick.

The rock quality of the marble is ranked from 42 to 57 according to the RMR system and 3–7 according to the Q-index system. Both, therefore, indicate that the rock mass quality of this marble stratum surrounding the underground cavern is 'moderate'.

2.2 Design of the UPTACs for the Pillar

To prevent rock mass loosening from the pillar between the main powerhouse and the main transformer caverns, a reinforced supporting scheme was designed. It consists of (1) general mortar rock bolts of 6 and 9 m in lengths, 1.5 m in spacing; (2) 15-cm thick steel-fiber shotcrete; (3) five rows of UPTACs with 2,000 kN allowable tensile load at a horizontal spacing of 3 m (Fig. 1).

Each anchor cable consists of 13 steel strands, and each strand is made up of seven threads (seeing Fig. 1). The threads are of high strength 40SiMn steel produced by cool drawing. The cable is wrapped in a bellows seal and filled with waterproof grease, then fixed inside the drill hole by a centering rack. Because the axis of the thru-anchor cable is not installed perpendicular to the surfaces of the pillar, a 20–40-cm thick C35 concrete base was placed on the sidewall surface and fixed with fixing bolts, then a quadrate steel subplate (0.4 m wide, 15 mm thick) was fixed on the flat end of the concrete base. The steel strands were then installed on the steel subplate using an anchoring device. An iron cap filled with waterproof grease was welded to the steel subplate to protect the anchoring device and the tips of the strands.

During the top-to-bottom excavation of the main powerhouse and the transformer cavern, the prestressed thru-anchor cables were installed in succession after the primary support installation (bolts and shotcrete) had been completed and the level of the opening floor was lower than the intended level of the cable rows. The preload of the UPTACs for the first and second rows was set at 1,600 kN, and the preload for rows 3–5 was set at 1,400 kN.

3 Disabled Anchor Cables

After the excavation of the caverns was completed, in situ monitoring data showed that some working loads of the UPTACs installed inside the pillar were beyond the design limit. A comprehensive field inspection was carried out in September 2010. Many disabled thru-anchor cables were found to have partially weakened working capability and were found inside the pillar in various modes of failure, as discussed below.

3.1 Observed Failure Modes of Anchor Cables

The observed failure patterns of the UPTACs in the pillar can be summarized as follows:

- Dislocation of iron cap: the iron cap, which was welded to the anchor base during installation, had become loose or detached from the anchor base because of the impact of the dislodged steel strand (Fig. 2a).
- Strand penetration through the iron cap: the abrupt release of elastic strain produced by a sharp break of the steel strand caused the strand to pierce the iron cap (Fig. 2b).

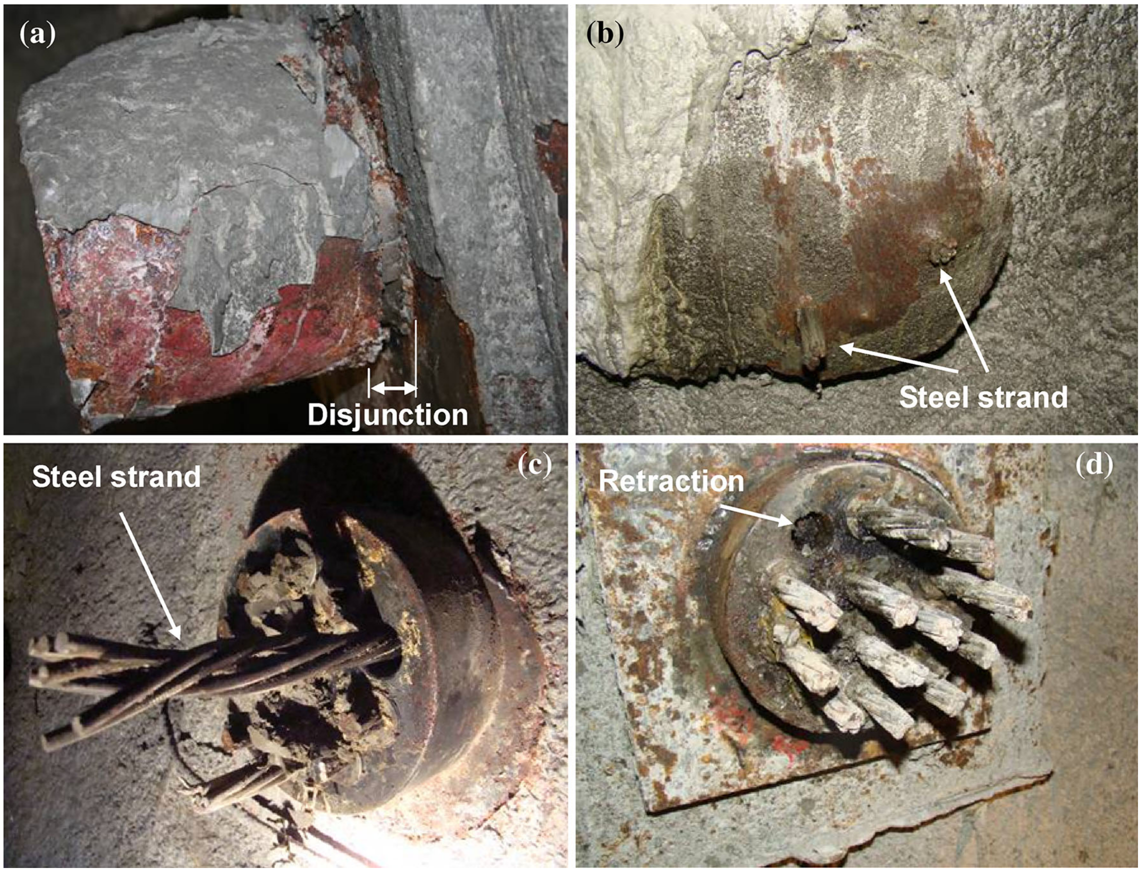

Fig. 2 Observed failure modes of disabled UPTACs in field: **a** disjunction of iron cap, **b** strand penetration through the iron cap, **c** ejection of steel strand, **d** retraction of steel strand

- Ejection of steel strand: the failed steel strands were expelled abruptly from the cable and the iron cap had fallen off (Fig. 2c).
- Retraction of steel strand: the steel strands retracted into the rock hole because of increased tensile force (Fig. 2d).
- Partial failure of cable: some steel strands of the cable broke while others remained intact (Fig. 2c, d).

The field investigations indicated that 38 out of 193 cables failed in the UPTACs within the rock pillar. Among the failed cables, 16 were in the first row, 18 in the second row, and 4 in the third row.

3.2 Failure Characteristics of the Disabled Steel Strands

To study the failure patterns of the anchor cables, i.e., shear or tension, three steel strands of the disabled anchor cables were pulled out from the pillar. The extracted segments of the failed steel strands were 7.6, 4.9, and 9.7 m long. The rupture faces of the threads in each steel strand were not in the same plane, but at random intervals, approximately 2–3 cm apart (Fig. 3a). Moreover, the rupture faces of the steel threads were rough and showed local necking behavior, similar to the tensile failure characteristics observed in studies of steel wires or anchor bolts (Crosky and Hebblewhite 2003; Li 2012).

The thread specimens were cut into 20-cm lengths from the disabled steel strands for tensile strength testing (using a MTS 8.15) during which the threads were strained at a rate of 0.1 mm/min. The experimental results showed local necking behavior and rough rupture faces were observed after thread failure (Fig. 3b). From the failure characteristics alone, our experimental laboratory results support the assumption that the in situ strands failed under tension.

3.3 Field Documentation of the Anchor Cable Failure Process

Some prestressed thru-anchor cables were selected for monitoring, and load cells were installed at their base during processing installation. Typical field monitoring results show that the load of a failed prestressed cable

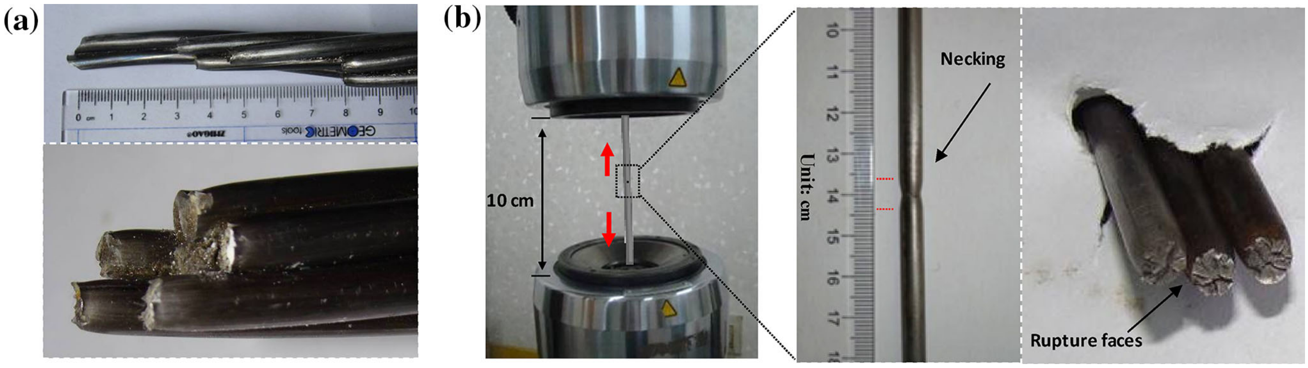

Fig. 3 Rupture faces of disabled steel strands in field (a) and break faces of steel threads in laboratory tensile experiments (b)

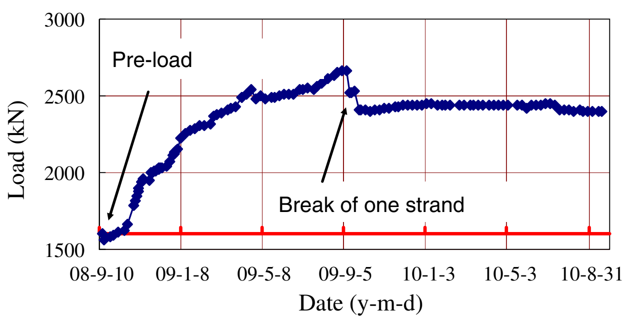

Fig. 4 Temporal loading curve of a typically disabled prestressed anchor cable

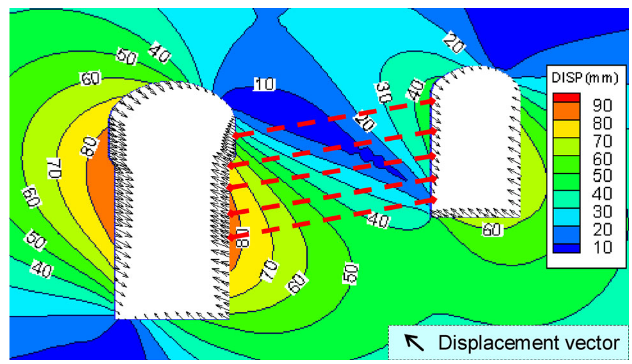

Fig. 5 Numerical displacement contour and vector of surrounding rock

increased to approximately 2,667 kN and then abruptly decreased to 2,402 kN (Fig. 4).

Subsequent examination of this monitoring UPTAC indicated that only one steel strand of the cable had broken during the excavation process of the main powerhouse and the main transformer cavern—suggesting that the continuous rise in tensile load of this cable induced rupture of the steel strand during the cavern excavation phase.

3.4 Main Causes of UPTAC Failure

The three major causes of cable failure in the Jinping II underground caverns are summarized in this section based on the in situ investigation and mechanical analysis.

1. Significant relaxation of sidewall during excavation of the main powerhouse and main transformer caverns: after installation of the UPTAC, the subsequent excavation of the main powerhouse and the main transformer cavern induced displacement release of the pillar, as confirmed by the results of numerical simulations (Fig. 5, based on Feng and Hudson 2011). In Fig. 5, the displacement contour map was calculated by simulating the opening of the Jinping II underground caverns. In the simulation of Feng and Hudson (2011), the stability analysis of the mid-pillar included verification of both the constitutive model and mechanical parameters based on the measured depth of the damage zone and the measured displacement of surrounding rock (Jiang et al. 2013). Caused by reverse movements of the two side faces of the pillar, the anchor bases that were installed on the surface of the sidewall moved in opposite direction to each other; thus, extending the unbonded anchor cable, resulting in an increased tensile stress of the cable.
2. A notable difference between the elastic modulus of the steel strands and the rock: the compressive elastic modulus of the marble rock mass in the caverns is in the range of 8–12 GPa, but the tensile elastic modulus of the steel strands is typically 180–200 GPa, approximately an order of magnitude higher than that of the rock mass. Therefore, a small relaxing displacement of the pillar can clearly induce significant loading increases through deformation transfer from the rock mass to the anchor bases.
3. The initial pre-stress ratio of the UPTACs was high: the pre-stress ratio (initial preloading stress/designed tensile strength) of the UPTACs in the first and second rows was 80 %; therefore, allowing for only a

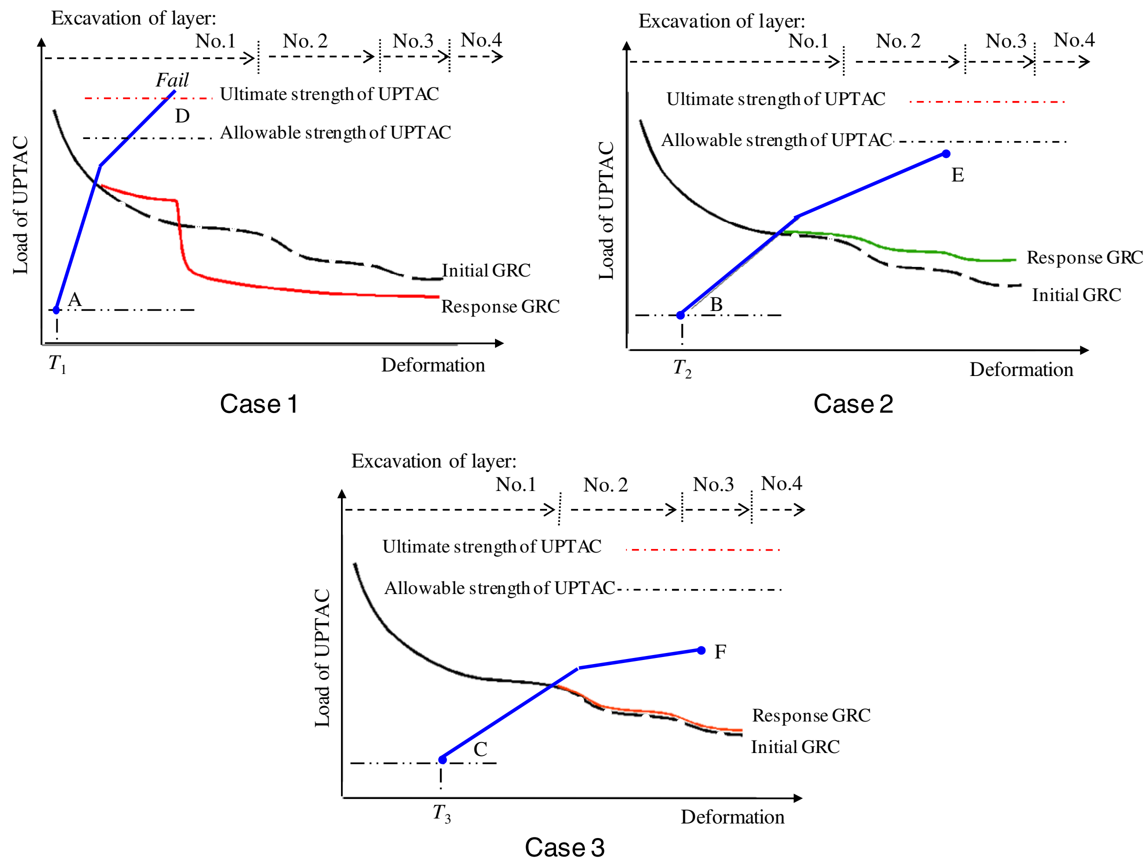

Fig. 6 Supporting opportunity for UPTAC-based on ground reaction curve (GRC) (based on Carranza-Torres and Fairhurst 2000)

remaining 20 % margin for stress increase in the tensile capacity of the UPTACs in these rows. For example, the inspected UPTAC load increased from approximately 1,598 kN (pre-load) to 2,667 kN, as shown in Fig. 4, i.e., an increment ratio >20 %. Therefore, the actual working stress of the anchor cable easily exceeded the permissible design strength and the ultimate strength of the steel strands whenever the released displacement of the reinforced rock was comparatively large.

4 Discussion

Understanding the causes of UPTAC failure is important for future design strategies along with the current empirical knowledge regarding the support time, the prestressed ratio, and the time-dependent effects on UPTACs. In large underground caverns with several opening layers or phases, the deformation release of the surrounding rock due to unloading relaxation must be assessed carefully when determining the prestressed ratio and the supporting time of UPTACs.

Optimal conditions to prevent UPTAC failure include: (1) sufficiently high supporting strength of the UPTAC for the reinforced rock to become stable, (2) the final working stress of the UPTAC should not exceed the cable's allowable tensile strength. Therefore, the three key design parameters that must be considered for UPTACs are the prestressed ratio, the supporting time and the total allowable tension load. Carranza-Torres and Fairhurst (2000) produced a conceptual map to describe the convergence-confinement method between the support system and reactive rock convergence for a general tunnel. According to this concept, the ground reaction curve (GRC) of an UPTAC, which is sketched based on numerical simulation and typical displacement curves measure in an in situ rock mass, is presented in Fig. 6. Based on this curve, reasonable conditions for support using UPTACs lie within T_2 (Line BE), but not T_1 (Line AD), or T_3 (Line CF), as shown in Fig. 6. Outside of T_2, unfavorable conditions exist for UPTACs, which would likely lead to cable failure or inefficient use of the material strength of UPTAC.

5 Conclusions

An in situ failure investigation of UPTACs in large underground caverns shows that failure patterns occurred in various manners, including disjunction of the steel capping, strand penetration through the steel cap, and ejection of the steel strand from the cable. Field investigations and laboratory experiments indicated that the modes of failed anchor cables can be classified as tensile failure.

From an engineering point of view, our case study of the Jinping II underground project can provide references for optimal UPTAC design for use in similar, large underground environments. Careful design of the prestressed ratio for UPTACs is key for avoiding cable failure. Our study in the Jinping II underground caverns suggests that a prestressed UPTAC ratio of 0.6–0.7 is optimal for preventing cable failure. In addition, a suitable supporting time is another important factor. Field experience indicates that the conditions, where the support system of rock bolts and shotcrete has already been installed and the current excavation-induced deformation in the surrounding rock trends to convergence is optimal for supporting time. Finally, applying an even preload for each of the strands of the anchor cables assists in avoiding partial failure of UPTACs.

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