Study on unloading of overloaded prestressed anchors in an underground cavern complex

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\textbf{Abstract.} The influence of unloading of overloaded prestressed anchor cables in underground caverns on overall stability is discussed in this paper, including the theoretical background on the reinforcement effect of anchor cables, and quantitative estimates from numerical modeling of the influences of anchor cable force unloading on rock mass deformation and forces in the other adjacent support systems. The numerical model shows the same results as the recording during the site unloading test: unloading the force of overloaded anchors by about 50-150 tonnes has limited influence on rock deformation, stress adjustment, the depth of the plastic zone in the rock mass, and the forces on the adjacent rock bolts and anchors. From the perspective of the overall stability of the underground caverns, unloading the force of the overloaded anchors can be another solution in addition to replacing the overloaded anchors with new ones to meet the requirements of the design standard.

1. Introduction

Prestressed anchor cable reinforcement technology has been widely used in geotechnical engineering projects, such as underground caverns or slopes, in China and elsewhere. The purpose of installing prestressed anchor cables is to increase the local stability (blocks that were formed kinematically free) and increase the safety factor; reduce deformation of some specific geological structures, such as faults or shear zones; or increase the safety reserve for the overall stability of underground caverns or slopes. Studies of prestressed anchor cables through theoretical analysis, field monitoring, model tests, and numerical simulation have led to fruitful research by many scholars and engineers around the world, on topics such as cable loading mechanisms, structural design theory, or the interaction between tendons and surrounding rock\textsuperscript{[1-11]}. The monitoring results show that in low and medium in situ stress areas, the prestressed anchor cables in large underground cavern converge quickly after the completion of the excavation, and there are few cases in which the anchor cables are overloaded to exceed the design capacity. But in high in situ stress areas or where the rock mass quality is poor, the load on some installed prestressed anchor cables continues to grow as excavation is completed, resulting in excessive stress or even failure of the anchor cable support.
According to codes and standards, if the prestressed anchor cable is overloaded, backup prestressed anchor cables should be installed, or the overloaded cable should be unloaded below the design force capacity to satisfy the requirement while at the same time maintaining the safety of the cavern and the slope.

Although prestressed anchors have been widely used in many civil engineering projects for a long time, due to the complexity of geological conditions for different projects, a unified understanding of the mechanism of anchor cable reinforcement has not yet been formed. Research on the interaction mechanism of the surrounding rock and the anchor cable, stress characteristics, and behavior of tendons is still insufficient, especially for evaluating the influence of unloading the overloaded tendons on cavern stability.

Whether unloading overloaded anchors or installing backup anchors in the caverns, maintaining the stability of the surrounding rock mass and the long-term safety of the support system is paramount. A comparison of the two solutions for overloaded anchor cables, from the standpoints of operability, implementation difficulty, and economic factors, indicate that unloading is the better choice. This work first presents a study of the influence of unloading the overloaded anchors on the stability of underground caverns using theoretical formulas and a numerical model. Subsequently, those results are verified by data recorded during site unloading testing in an underground powerhouse of a pumped storage project in Israel. Those research results provide a reference for the design of an anchorage system and for evaluation of the long-term safety of a rock mass in a complex geological environment.

2. The reinforcement mechanism of Prestressed anchor cables

2.1. Prestressed anchor cable function

Rock openings cover a wide spectrum of configurations and applications, including transportation tunnels, hydropower production, pressure headrace tunnels, machine hall chambers, pumped storage projects, energy storage schemes, and different types of mining infrastructure. Invariably, rock behavior and support design have a direct relation to the engineering aspects of the project, because all underground works are typically done in a rock mass which is initially stressed, so any openings will cause changes in the initial state of stress.

A rock mass is generally heterogeneous and anisotropic. Rock discontinuities and some faults or shear zones will be intersected. Often, during the construction of underground caverns there could be large deformation and stability problems associated with excavation.

Anchors and cables used as support develop their anchorage effect according to the following mechanisms[12]: (a) suspending the dead weight of rock slabs or fastening loose blocks to stable layers, (b) providing normal stress on the rock surface to clamp bedding planes together and develop composite beam action, (c) introducing a confining pressure to increase shear resistance with arch response whereby the rock becomes self-supported, and (d) preventing key blocks from becoming loose.

![Diagram](image)

**Figure 1.** Support mechanisms of anchor cables.
The stability of openings essentially depends on the shear strength of the jointed rock mass as excavation proceeds. Failure is imminent when the rock mass strength is exceeded. Installed reinforcement (anchors, bolts, or rebars) ties together the rock mass by increasing the confining pressure in the rock adjacent to the opening, making the rock mass self-supported. Initially, by tensioning the anchors, the rock mass is compressed between the anchor ends. Subsequently, tensioning any unstressed reinforcement that occurs due to dilation of the rock mass after excavation produces the same effects.

2.2. Support pressure estimated by an empirical formula
Except for specific wedge/block issues in underground caverns, the maximum pressure provided by the support can be estimated by empirical formulas (Carranza-Torres, 2000)\(^{[13]}\):
(1) Shotcrete/concrete

\[
p_s^{\text{max}} = \frac{\sigma_{cc}}{2} \left[ 1 - \frac{(R-t_c)^2}{R^2} \right]
\]

where
\( p_s^{\text{max}} \) is the maximum pressure provided by the support (MPa);
\( \sigma_{cc} \) is the unconfined compressive strength of the shotcrete or concrete (MPa);
\( t_c \) is the thickness of the ring (m); and
\( R \) is the external radius of the support (m) (taken to be the same as the radius of the tunnel).

(2) Rock bolts/cables

\[
p_s^{\text{max}} = \frac{T_{bf}}{s_c s_l}
\]

where
\( T_{bf} \) is the ultimate load obtained from a pull-out test (MN);
\( s_c \) is the circumferential bolt spacing (m); and
\( s_l \) is the longitudinal bolt spacing (m).

Consider the example of a circular tunnel with a diameter of 12 m in a hydrostatic in situ stress state (10 MPa). As listed in Table 1, the support pressure provided by shotcrete, rock bolts, and prestressed anchors can be estimated according to Eqs. (1) and (2). The ratio of the support pressures for the three types of support is 1:0.4:0.1, respectively. The support pressure of the prestressed anchor is only 10% of that of the shotcrete. From a global perspective, unloading the force in the anchor cables, or even not installing anchor cables, might have little influence on the total support pressure, and it might have little influence on the overall stability of underground caverns.

Table 1. Empirical estimates of support pressure.

| Support type         | Support parameters                                    | Support pressure (\( p_s^{\text{max}} \) MPa) | Note                |
|----------------------|------------------------------------------------------|-----------------------------------------------|---------------------|
| shotcrete            | B40                                                  | 0.515                                         | \( \sigma_{cc}=25 \) MPa |
|                      | \( t_c=20 \) cm                                      |                                               |                     |
|                      | Length=9 m, Diameter=32 mm                           |                                               |                     |
|                      | @1.2x1.2 m                                          |                                               |                     |
| rock bolts           | Design capacity 90 tonnes                            | 0.208                                         | \( T_{bf}=0.300 \) MN |
|                      | @4.0x4.0 m                                          |                                               |                     |
| Pre-stressed anchor  |                                                      | 0.056                                         | Un-bonded           |

3. Analysis of unloading force of prestressed anchor cables

3.1. Project introduction
The Kokhav Hayarden Pumped Storage Power station project (hereinafter referred to as the KHPSP) is located near the village of Gesher in northern Israel, near the Jordan River Valley, 120 km from Tel Aviv. The underground powerhouse complex includes the main powerhouse, auxiliary powerhouse, transformer hall, busbar tunnel, main access tunnel, emergency cable tunnel, and construction adit. The size of the powerhouse is 82.2 m × 18.0 m × 43 m (length × width × height).

In the powerhouse complex, the rock mass lithology includes strong basalt, vesicular basalt (bs-weak), and pyroclastic layers composed of tuff and breccia, which is a mixture of basalt clasts and clay or volcanic ash. A number of faults (f18, f22, etc.) intersect the powerhouse cavern. The rock mass classification is class III, class IV, and locally class V. The depth is about 400 m. The in situ stress regime is strike-slip (i.e., $S_{H} > S_{V} > S_{h}$). The maximum horizontal stress, $S_{H}$, with the direction of N11°W, is in the range of 12 MPa to 15 MPa.

3.2. Numerical model evaluation

To investigate the influence of unloading prestressed anchor cables, 2D and 3D numerical models of the powerhouse cavern complex were simulated in FLAC3D[14]. In each model, the excavation and support process was simulated step by step. The numerical models are shown in Figure 2. The unbonded prestress anchor cables are modeled by cable structural elements with bonded and free lengths.

![Figure 2. Numerical models.](image)

The geotechnical parameters of the rock mass are listed in Table 2. For bs-weak class III and bs-strong class III/IV rock mass, the post-peak behavior was approximated with a strain-softening constitutive model. The residual strength is approximated assuming residual cohesion to be zero. The residual friction angle was kept the same as for the peak strength. For weak, pyroclastic class IV rock mass, the elastic perfectly plastic Mohr–Coulomb model was used[15–17].

The numerical model, geotechnical parameters of the rock mass, in situ stress conditions, etc. have been back analyzed and verified during the six main excavation stages of the powerhouse. A load comparison of typical anchor cables installed in the powerhouse between monitoring on-site and prediction by the numerical model is shown in Figure 3.
Figure 3. Load comparison of monitoring results and values predicted by the numerical model. After finishing the excavation of the powerhouse cavern complex, two cases were analyzed for the overloaded tendons, with an axial force of more than 90 tonnes (design capacity): Case A, unloading the axial force of one overloaded tendon to 80 tonnes; and Case B, unloading the axial force of all the overloaded tendons to 80 tonnes.

Table 2. Geotechnical parameters of the rock mass.

| Rock lithology         | UCS /MPa | GSI | m | Modulus of rock mass /GPa | Cohesion /MPa | Friction angle /° |
|------------------------|----------|-----|---|--------------------------|---------------|------------------|
| Bs-strong, class III   | 101.3    | 45  | 25| 7.50                     | 2.70          | 47.01            |
| Bs-weak class III      | 50.81    | 43  | 25| 4.76                     | 2.05          | 41.08            |
| Bs-weak, class IV      | 33.9     | 39  | 20| 3.09                     | 1.55          | 34.80            |
| Pyroclastic, class IV  | 8.8      | 34  | 12| 1.18                     | 0.70          | 19.76            |

The numerical investigation procedure has the following seven steps: 1) Building the 2D and 3D numerical models with consideration of the rock lithology, faults, and main joints according to the geological model; 2) Initializing the in situ stress conditions of the model; 3) Documenting the deformation and stress of several typical points around the cavern profile; 4) Simulating the whole process of excavation and support of the underground powerhouse cavern complex step by step according to the design construction scheme; 5) Checking the load for each of the selected installed anchor cables and identifying the overloaded anchor cables after the excavation is complete; 6) setting the axial force of the overloaded anchor cables to 80 tonnes by built-in scripting language of FLAC3D in the numerical model, and then letting the numerical model iterate to equilibrium again; 7) checking the increment of the deformation, the stress, and the depth of the plastic zone after unloading the overloaded anchor cables.

For case A which is only unloading one overloaded anchor cable: a) the axial force of overloaded anchor cables in the 2D numerical model is reduced by about 48.90 tonnes from 128.90 tonnes to 80 tonnes, the displacement increment in the 2D model is less than 0.10 mm, and the stress adjustment in the rock mass surrounding the location of the unloading anchors is less than 0.12 MPa; b) the axial force of overloaded anchor cables in the 3D numerical model is reduced by 30.30 tonnes from 130.30 tonnes to 80 tonnes, the displacement increment in the 3D model is 0.10-0.32 mm, and the stress adjustment in the rock mass is 0.10-0.21 MPa; c) the depth of the plastic zone has no change for both the 2D and 3D models.

For case B which is unloading all the overloaded anchor cables: a) the axial force of overloaded anchor cables in the 2D numerical model is reduced by 1.10-48.9 tonnes, the displacement increment in the 2D model is 0.50-2.10 mm, and the stress adjustment surrounding the location of the unloading anchors is 0.02-0.20 MPa; b) the axial force of overloaded anchor cables in the 3D numerical model is reduced by 1.20-30.3 tonnes, the displacement increment in the 3D model is 1.00-5.80 mm, and the stress adjustment is about 0.12-0.35 MPa; c) the depth of the plastic zone has no change for both the 2D and 3D models.
The detailed results are shown in Table 3 and Figure 4. It was also found that if unloading only one anchor cable, the influence range is less than 2 m. Based on the numerical results, unloading of the overloaded anchor cables has little influence on the deformation, stress, or depth of the rock mass.

### Table 3. Statistical results of rock mass responses before and after unloading force on the tendons.

| Model | Study case | Axial Force before unloading to 80 tonnes /tonnes | Displacement increment /mm | Stress adjustment /MPa | Depth of plastic zone /m |
|-------|------------|-----------------------------------------------|-----------------------|---------------------|------------------------|
| 2D model | Case A | 128.90 | 0.00-0.10 | 0.00-0.12 | no increase |
|        | Case B | 83.00-128.90 | 0.50-2.10 | 0.02-0.20 | no increase |
| 3D model | Case A | 130.30 | 0.10-0.32 | 0.10-0.21 | no increase |
|        | Case B | 84.30-130.30 | 1.00-5.80 | 0.12-0.35 | no increase |

**Figure 4.** Displacement increments after unloading the prestressed anchor cables.

### 3.3. Site testing

In the KHPSP, before unloading all of the overloaded anchor cables, three installed prestressed anchor cables were chosen to be tested after finishing the excavation of the second layer of the powerhouse. During and after unloading testing, nearby load cells and deformation on the anchor head were monitored by dial gauge. The arrangement of the monitoring instruments for No.17, which is one of the three tested unloading anchors, is shown in Figure 5.

**Figure 5.** Monitoring arrangement during unloading testing of anchor cable.
The testing process is to first prestress the anchor cable from 0 tonnes to 156 tonnes with seven subloading steps, then to unload the axial force to 120 tonnes, 80 tonnes, 40 tonnes, 10 tonnes, 5 tonnes, and 0 tons. Each unloading round is held for 10-20 min and data is logged for all the monitoring devices every 6 minutes. The testing results are shown in Figure 6.

During the loading of anchor cable No.17 from 0 to 156 tonnes: a) the displacement increment of the rock mass was 0.0-0.04 mm; b) the stress adjustment in the rock bolts is 0.0-0.1 MPa; c) the force increment of nearby anchor cables is 0.0-0.01 tonnes.

During the unloading of anchor cable No.17 from 156-0 tonnes: a) the displacement increment of the rock mass is 0.0-1.38 mm; b) the stress adjustment in the rock bolts is 0.06-0.5 MPa; c) the force increment of nearby anchor cables is 0.0-0.02 tonnes.

![Diagram a. The curve of force of testing anchor cables and the dial gauge displacement on anchor cables head](image1)

![Diagram b. The curve of force of testing anchor cables and the displacement of nearby extensometers](image2)

![Diagram c. The curve of force of testing anchor cables and the stress of rock bolts](image3)
4. Conclusion

The influence of unloading anchor cable axial force on cavern stability during the construction stage was studied by theoretical analysis, numerical modeling, and site testing. For the overall stability issues, theoretical analysis shows that the supporting force provided by the prestressed anchor cable is small relative to that of the other support components such as shotcrete, concrete, and rock bolts. Numerical analysis reveals that when unloading the overloaded anchor cables to a value below the design capacity, which is decreasing the axial force by about 5-50 tonnes, there is a very limited increase in deformation of the surrounding rock, only within several millimeters. The depth of the plastic zone does not change, and the adjustment of the stresses in the rock mass is very small. Site testing in the powerhouse of a pumped storage project in Israel confirmed the small effect of unloading the axial force of prestressed anchor cables from about 150 tonnes to 0 tonnes.

Unloading the force of the overloaded anchor is one suggested solution for overall stability issues of an underground cavern project because it is a practical engineering measure, which can make the designed support system meet the requirements of standard specifications and ensure cavern stability simultaneously. It is recommended that anchor cable unloading should be implemented by gradual unloading of one cable at a time. The relocking force is recommended to be no less than the original locking value.

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