Landslides
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A modified lift-off test for restressing anchors of a rehabilitated landslide slope

Abstract This study proposed a modified lift-off test that enables evaluation of the anchoring condition (anchored capacity or creep ratio) during the investigation of the residual anchor load and facilitates the restressing of anchors. To verify the applicability of the proposed measure in practice, a case study of the rehabilitated landslide slope of the T16 support tower of the Taipei Maokong Gondola System was conducted, a two-stage procedure that simultaneously facilitated the investigation and rehabilitation of an anchored slope with load loss. Results of an investigation of the residual load acting on 619 anchors indicated that the average load loss of the anchors was approximately 36% compared with the design load. In conventional design, approximately 223 extra anchors must be installed in the study area. However, the corresponding number in the proposed measure is about one-fifth the number of anchors required in the conventional approach. This paper emphasizes the merit of using the modified lift-off test in reducing construction time and construction costs in slope rehabilitation. Furthermore, the proposed rehabilitation measure adopted in this study did not involve adding many concrete structures to the original anchored slope. Thus, these measures are environmentally friendly and contribute to sustainable development.

Keywords Ground anchor · Landslide case study · Lift-off test · Residual load · Slope rehabilitation measure

Introduction

Ground anchors have been widely used to reinforce high-risk slopes and mitigate large-scale landslides (Hobst and Zajic 1983; Muraro et al. 2015). However, stressing load is applied to the ground anchors to drive the performance of such an active tieback structure. Therefore, the trend of load change (increasing or decreasing) on ground anchors directly represents the performance of the ground anchors and indirectly represents the safety of the slope. The characteristic of the loading change on the ground anchor is mostly progressive, and it can provide insights for conducting proper maintenance and rehabilitation plans (Cheng et al. 2022).

Typically, the load distribution on ground anchors is complex, specifically the tensile stress acting on tendons or shear stress between anchor-grouted interfaces, which might change over time (Chen et al. 2021). This results in a long-term loading change, either increasing or decreasing. The level of load increase or load loss in the ground anchor is closely related to the stability of the anchored slope. An increased anchor load suggests potential sliding of the anchored slope. Typically, slope stability analysis is required to confirm the safety of the slope. However, in situations necessitating emergency measures, engineers often employ dewatering, improved slope drainage, and construct additional reinforced structures to reduce the risk of sliding on anchored slopes (Popescu and Sasahara 2009). In contrast, load loss is usually caused by various factors such as material properties, construction, and environmental factors, including the creep of the ground anchor system (e.g., slope, anchor, and grouted material), differential settlement between the slope surface and tieback structure, stress resilience of the anchorage device, and corrosion of the anchorage or steel strand (Shi et al. 2019; Liao et al. 2019). The mentioned factors highlight that the causes of load loss are more complex than those of load increase, and the measures that can be implemented to rehabilitate an anchored slope are not as direct as those for actions under load increase. Identifying the cause of load loss is crucial before determining the rehabilitation measures for anchored slopes. Some studies have employed physical model tests or in situ tests to investigate the loading behaviors of ground anchors. They interpreted the cause (e.g., creep of geomaterials, creep of the ground anchor system, stress resilience of anchorage device, the construction, and environmental disturbance) of load loss based on monitored results and established theoretical methods for predicting long-term load loss (Benmokrane and Ballivy 1991; Chen et al. 2002; Kim 2003; Shi et al. 2019; Zhu et al. 2022). These studies have provided an understanding of the load loss behavior of ground anchors and promoted improvements in the functions of ground anchors.

In the design concept for ground anchor construction (BSI 2013), engineers find total load losses acceptable, provided that the stress relaxation of assembly components (e.g., anchorage head and steel strands) and creep of the ground anchor system do not exceed 20% of the design load (T_w). This is because the safety coefficient for these risks has already been considered in the lock-off load ($T_o = 1.2\ T_w$). However, the long-term behavior of on-site ground anchor may be influenced by construction technology and environmental disturbances (e.g., corrosion of anchor components, weathering of geomaterials, and compression/settlement of subsoil). As a result, an anchor inspection program is often implemented to assess the long-term performance of existing ground anchors. If corrosion is identified as the cause of load loss, immediate anti-corrosion measures are adopted to prevent further anchor corrosion. Additionally, a suitable number of ground anchors, micro piles, or other reinforced structures, determined based on the level of load loss, are installed on the slope for reinforcement (Liao 2011; Liao and Cheng 2011, 2017). Conversely, if there is no corrosion in the anchor assembly and the material creep of the ground anchor has been ruled out, the load loss may be attributed to environmental disturbance (e.g., weathering of geomaterials and compression/settlement of subsoil). In such cases, where there is no immediate danger to slope stability, restressing measure, as reported by Littlejohn and Bruce (1975, 1977), can be applied to increase the anchor load. This approach is more economical, easier to implement, and more environmentally friendly compared to other methods for rehabilitating the existing slope anchors.

The restressing measure applied to existing anchors should not be arbitrary. Completion of the anchor inspection program is essential to ensure that anchor components remain unaffected by corrosion. Simultaneously, the anchoring condition (creep ratio, also known as the slope of creep displacement vs. the decimal logarithm of time) of the existing anchor intended for restressing must be assessed and verified to be within an acceptable range to ensure its capacity for restressing. Once this requirement is met, this study proposes a modified lift-off test for restressing the existing ground anchors. This modified lift-off test allows for the evaluation of anchoring conditions during the investigation of the residual anchor load, facilitating the restressing of anchors (i.e., increasing the load to compensate for any loss if necessary). This modified lift-off test requires the same equipment and involves similar steps as conventional lift-off tests. To demonstrate the applicability and practicality of the modified lift-off test, this study explains the principles for evaluating anchoring conditions and restressing procedures incorporated into the modified lift-off test. Subsequently, the modified lift-off test was conducted in a rehabilitated landslide case study, which included function inspection, anchored capacity evaluation, and restressing of the slope anchors. This highlights the advantages of the proposed measure in environmentally friendly rehabilitation of anchored slope and sustainable development.

Evaluating the anchoring condition and the restressing of existing anchors by using the modified lift-off test

The lift-off test is commonly employed to verify the residual load of existing anchors (BSI 2013). In a ground anchor inspection program, this method is utilized alongside other steps, such as visual inspections of anchor protection caps and anchorage head components, as well as borescope inspections of strands under anchorage heads. These steps collectively contribute to determining the functional status and remaining capacity of the ground anchor (Liao et al. 2019). When the above steps indicate that the ground anchor is not significantly affected by corrosion, and the anchor load loss can be primarily attributed to the creep of anchor material or construction factors resulting in stress readjustment between the slope and the ground anchors, a modified lift-off test becomes a viable alternative measure. This test encompasses the investigation of the residual load, the evaluation of anchoring conditions, and the restressing of existing ground anchors. The working principle and restressing procedure details of the modified lift-off test are provided in the following content.

Principle of the proposed modified lift-off test

Figure 1 illustrates a typical layout of lift-off devices and the corresponding load-displacement curve. In Fig. 1b, the residual load (T_r) represents the equilibrium force between the slope and the anchors, serving as a quantification of the ground anchor performance. This performance is an integrated value reflecting the functional status, encompassing various strand corrosion conditions. Under type 1 condition, where strands are severely corroded and prone to breakage due to uneven stress during the lift-off test, the T_r value is typically equal to the breaking load of the strands but significantly less than the anchored load of the ground anchor. This condition is defined as anchor failure. In type 2 condition, the strand exhibits light corrosion, resulting in a marked decrease in T_r but maintains a certain load level. In such cases, the maximum lift-off load (T_L) should be within the range of 1.1–1.2 times the residual load (1.1–1.2 T_r). Exceeding this range increases the risk of strand breakage. For type 3 condition, where the strand experiences no corrosion and the T_r does not decrease, T_L can be increased to the designed load (T_w) or 1.1–1.2 times the designed load (1.1–1.2 T_w). Table 1 summarizes these conditions and provides suggested T_L values in the modified lift-off test for existing ground anchors with varying levels of corrosion.

The anchoring condition of ground anchors with load loss in type 2 and type 3 conditions is evaluated synchronized with the lift-off test to determine whether restressing is permissible. As depicted in Fig. 1b, the maximum lift-off load (T_L) is applied after obtaining the T_r values. T_L is maintained for 10 min, and the displacement of the anchorage head is recorded at 1 min (S_1) and 10 min (S_{10}) into the test. Subsequently, the actual creep ratio ($k_{s(10)}$) under the maximum lift-off load (T_L) for the anchor can

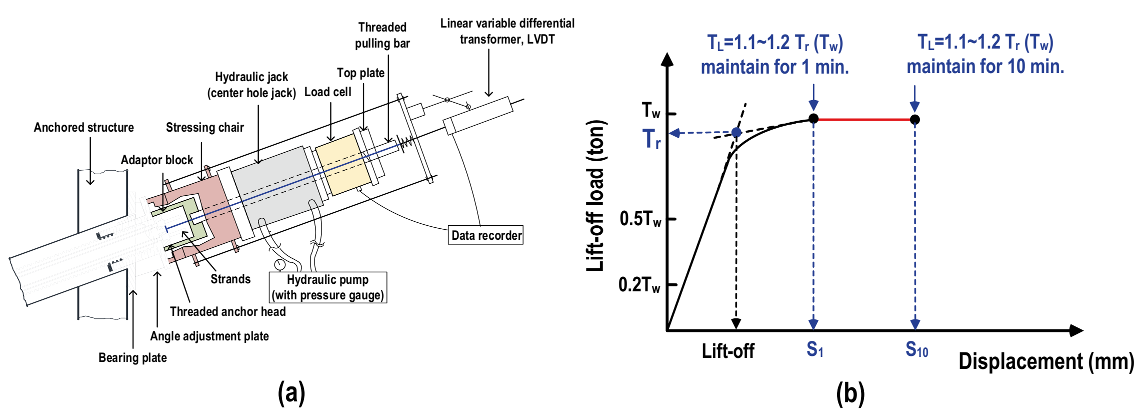
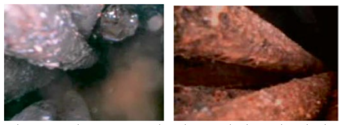
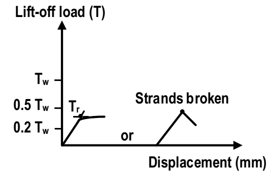
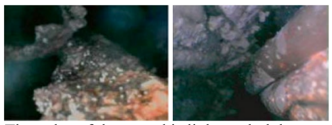
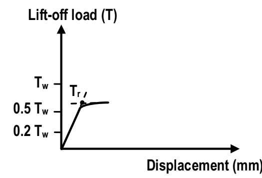
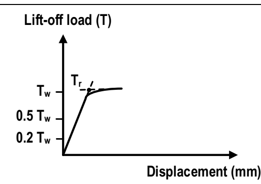


Fig. 1 **a** Typical device layout in the lift-off test and **b** load-displacement curve obtained from the lift-off test

Table 1 Suggested maximum lift-off load in the modified lift-off test under different strand corrosion conditions

Classification	Strand corrosion condition	Typical lift-off curve	Suggested maximum lift-off load (T_L)
Type 1	 The strands are completely eroded, and a dark brown color or rusty texture is found on the strand surface.		Anchor failure and invalid anchor, no suggested lift-off load.
Type 2	 The color of the strand is light or dark brown. The strand surface is smooth, or a rust texture is observed.		$T_L = 1.1 \sim 1.2\ T_r$
Type 3	 No abnormal condition is observed.		$T_L = T_w$ or $T_L = 1.1 \sim 1.2\ T_w$

be calculated by Eq. (1). While the duration for which T_L is maintained can be extended, it should not be overextended, as the anchoring conditions of a ground anchor with good function are typically reflected within a short period.

$$k_{s(10)} = \frac{s_{10} - s_1}{\log(10\ \text{min.}) - \log(1\ \text{min.})} \quad (1)$$

Evaluation of the anchoring condition (creep ratio) for existing ground anchors

In practice, all newly constructed anchors typically undergo an acceptance test to demonstrate their working performance. Taking Taiwan's road construction specifications on anchor construction as an example (MOTC 2014), anchors under a proof load (T_p) of 1.2 T_w should meet one of the following two conditions to pass an acceptance test. First, for operators who have not conducted a proofing test before construction, the creep ratio under T_p should be less than 1.2 mm for both permanent and temporary anchors. Second, for operators conducting a proofing test before construction, the creep ratio under T_p should be less than 1.5 and 1.8 mm for the permanent and temporary anchors, respectively. Therefore, for an existing permanent ground anchor with a certain degree of performance, the acceptable creep ratio ($k_{s(L)}$) under the maximum lift-off load (T_L) can be estimated using Eq. (2). Subsequently, a comparison is made with the $k_{s(L)}$ and $k_{s(10)}$ value. When $k_{s(L)} \geq k_{s(10)}$, it indicates that the anchoring condition of the ground anchor is in good condition, and restressing is permitted. Conversely, when $k_{s(L)} < k_{s(10)}$, it indicates that the anchoring condition of the ground anchor is in poor condition, and the anchor does not meet the criteria for restressing. In such case, restressing cannot be performed even if it observed no corrosion on the strand because of the potential risk of pull-off.

$$k_{s(L)} = \frac{T_L \times 1.2\ \text{mm}(or\ 1.5\ \text{mm})}{1.2\ T_w} \quad (2)$$

Restressing procedure for existing ground anchors

In summary, anchors experiencing load loss were classified as type 2 or type 3 conditions based on function inspections regarding corrosion. Restressing criteria are allowed for anchoring conditions evaluated that are deemed satisfactory ($k_{s(L)} \geq k_{s(10)}$) to compensate for the load loss. The restressing method can be categorized into the following two types.

- Restressing by removing wedges from anchorage: This restressing method, also known as conditional restressing, faces hindered when the exposed length of the strand is insufficient for

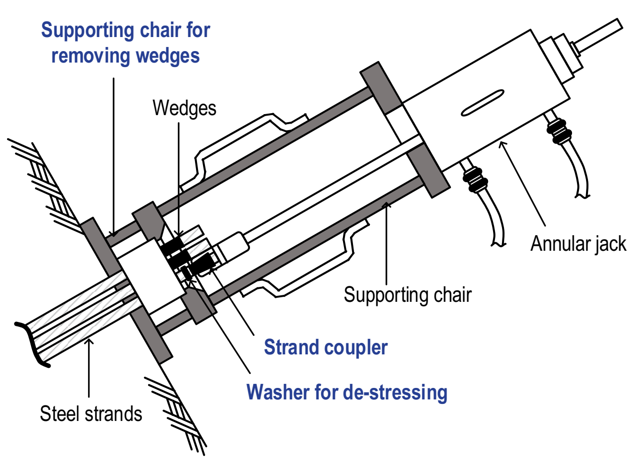


Fig. 2 Device layouts for the destressing and restressing of existing anchors with a short exposed length (modified from JAA (2008))

mounting a hydraulic jack and related stressing components. A dedicated device, as displayed in Fig. 2, overcomes the installation problem by using a lightweight annular jack, a strand coupler, a destressing washer, and a supporting chair for removing wedges (JAA 2008). However, performing restressing following the destressing (removal of the wedge using a strand gripper) may alter the engaged position of the lock-in wedges on steel strands, creating bite marks and resulting in a weak location of corrosion on the steel strands.

- Restressing concurrently with the lift-off test: This restressing procedure involves determining the residual load of the ground anchor using the lift-off test. If the anchor exhibits load loss, the anchoring condition is evaluated through a modified lift-off test. When the creep ratio corresponding to the residual load is deemed satisfactory (indicating good anchoring condition), stress can be applied and increased to the designed load by continuing the modified lift-off procedure. After the stressing has been increased to compensate for the load loss, the restressing process is completed by closing the gap between the anchor head and the bearing plate by using a split steel ring of adequate thickness (Fig. 3). The proposed method, developed by modifying the typical lift-off test, does not require dedicated equipment and does not alter the engaged position of the lock-in wedges on steel strands, thereby avoiding any risk to the weak location of corrosion on the steel strands.

History and site conditions of the case study

To confirm the feasibility of using the modified lift-off test for rehabilitating an anchored slope with anchor load loss, this study conducted field testing in a case study. The slope in question is situated downhill of the T16 support tower of the Taipei Maokong Gondola System in northern Taiwan. The following content offers details about the landslide history, remediation measure, geological conditions, monitored slope stability, and the evaluation of slope stability under various anchor loading conditions in the study area.

Landslide in the study area

In September 2008, a shallow-slope landslide occurred downhill of the T16 supporting tower of the Taipei Maokong Gondola System due to Typhoon Jangmi. This landslide was attributed to topographic changes (i.e., headward erosion), geological conditions (i.e., colluvial soil layer up to a thickness of 2–6 m), and heavy rainfall (i.e., cumulative rainfall reaching 500 mm within 24 h). As illustrated in Fig. 4a, the collapsed area had a length of approximately 230 m, a width ranging from 20 to 80 m, a total area of about 1.2 ha (12,000 m^2), and a landslide volume of roughly 30,000 m^3 (Yang et al. 2017; Nguyen et al. 2022). Significantly, the upper and lower edges of the landslide area contained crucial structures that needed protection. The upper edge provided stability for the base of the T16 support tower, while the lower edge ensured the safety of the residents' community of the slope. A comprehensive design was implemented for landslide remediation, involving the installation of various slope stabilization structures such as stabilizing piles, ground anchors, soil nails, horizontal and vertical water ditches for drainage, and wire meshes for hydroseeding (Fig. 4b).

Site conditions and geological properties

Before the landslide occurrence, the average slope in the study area was approximately 26°, and the attitude (strike/dip angle) of the rock layers was N50°–60°/SE10°–20°, forming a typical escarpment. Figure 5 displays the slope geometry and geological conditions in the study area before and after the landslide. The geological conditions in the landslide area consist of four layers: (1) a residual soil layer (R layer), (2) a mildly weathered shale layer (SH layer), (3) a blocky sandstone layer (SS layer), and (4) a layer comprising alternating sandstone and shale (SS–SH layer) or a layer containing interbedded sandstone and shale (SH/ss layer). The R layer, approximately 2–6 m thick, was the main sliding layer of the landslide, formed through the weathering and decomposition of sandstone and shale. It is mainly composed of silty sand and low-plastic silt, with average standard penetration test below count, SPT-N, values

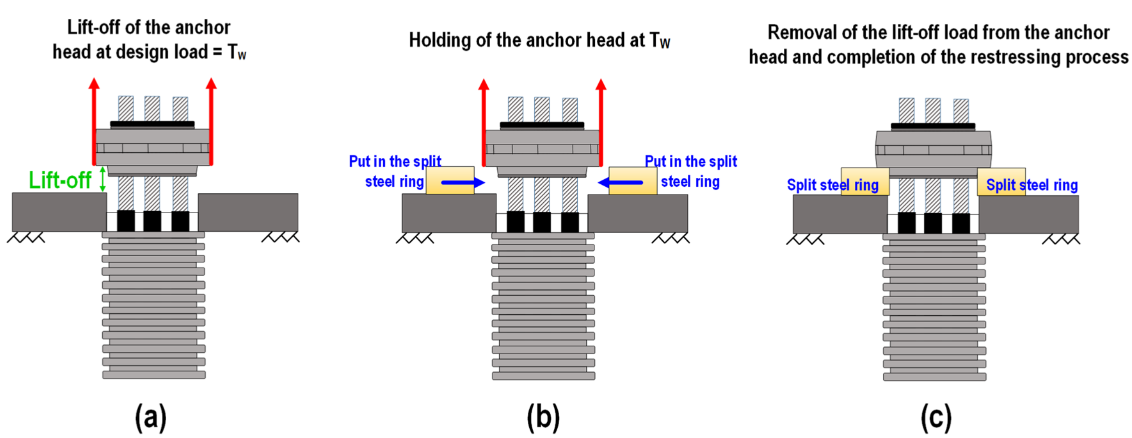


Fig. 3 Restressing of an existing anchor in the modified lift-off test: **a** lift off of the anchor head at the design load, **b** holding off the anchor head at the design load and placing a steel split ring into the gap between the anchor head and the bearing plate, and **c** removal of the lift-off load from the anchor head and the completion of the restressing process

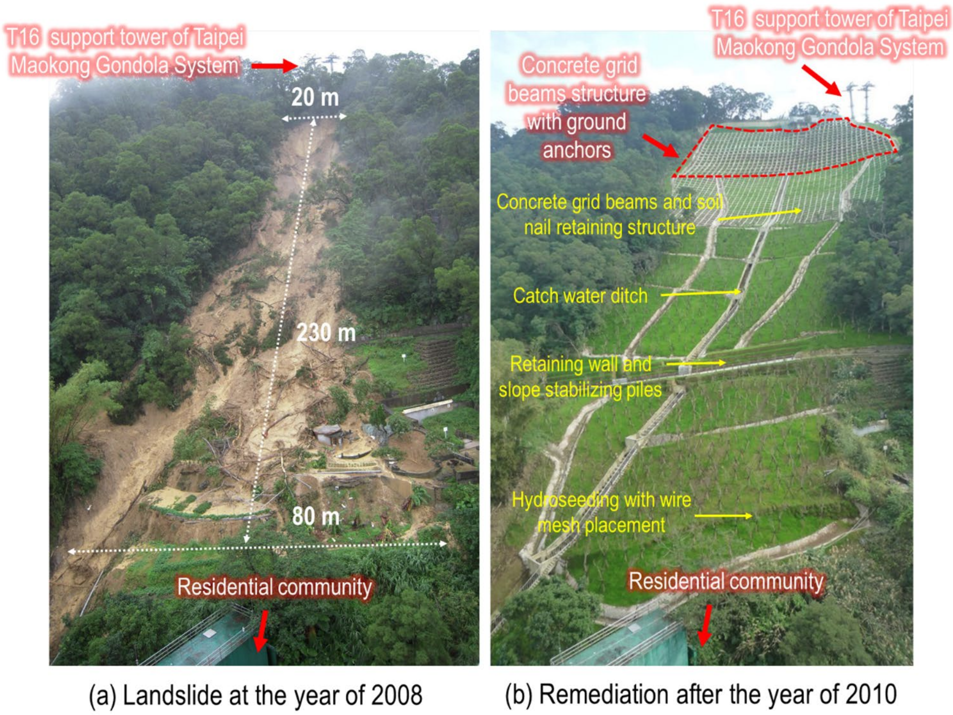


Fig. 4 Case study of the anchored slope near the T16 support tower of the Taipei Maokong Gondola System: **a** large-scale shallow landslide in 2008 and **b** remediation condition in 2010

being 21, a unit weight (γ_t) of approximately 20.5 kN/m^3, cohesion (c) of 6 kPa, and a friction angle (Φ) of 27 degrees. The SH layer, with a thickness of approximately 20 m and housing the base of the T16 supporting tower, has unit weight (γ_t), cohesion (c), and friction angle (Φ) of approximately 25.5 kN/m^3, 680 kPa, and 36 degrees, respectively. The SS layer, with a thickness of about 16 m, has a unit weight (γ_t) of approximately 24.5 kN/m^3, cohesion (c) of 256 kPa, and a friction angle (Φ) of 27 degrees. Finally, the layer comprising the SS–SH and SH/ss layers has a thickness of about 80 m, with unit weight (γ_t) of approximately 25 kN/m^3, cohesion (c) ranging from 300 to 450 kPa, and a friction angle (Φ) ranging from 30 to 32 degrees. Despite abundant runoff water on the slope surface, groundwater

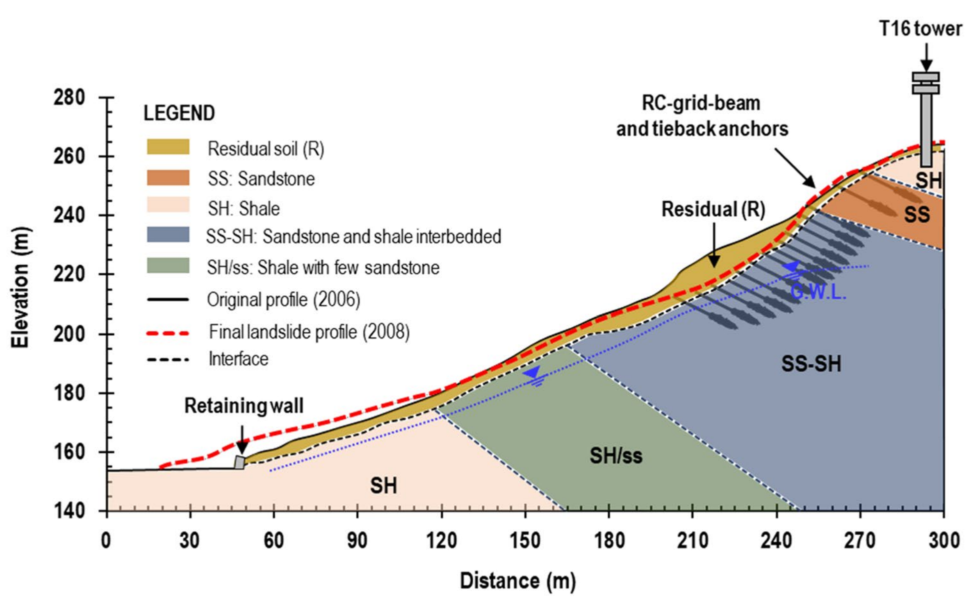


Fig. 5 Cross section of the geometry, geological profiles, and ground anchor installed on the anchored slope near the T16 support tower of the Taipei Maokong Gondola System

typically remains at a depth of 8–12 m with no apparent changes. This study focused on the anchored slope (concrete grid beam structure with ground anchors) marked in Fig. 4b because it is a crucial reinforcement structure for the base of the T16 supporting tower and the landslide area. A total of 619 ground anchors, each with a length of 25 m (including a free length of 15 m and a fixed length of 10 m), were installed on the slope. These anchors, design with a load (T_w) of 40 tons and double corrosion protection, were anchored into SS and SS–SH layers. However, a thin layer of residual soil exists below the concrete grid beam structure (Fig. 5).

Slope stability monitoring

Following the completion of the remediation work on the landslide area, various monitoring devices have been installed on the slope over the past decades. As shown in Fig. 6a, changes in water levels within the landslide area and the movement of the slope section were determined from observation wells and inclinometers, respectively. Additionally, the stress behavior of the ground anchors was monitored by 12 load cells mounted on the anchored slope beneath the T16 support tower (Fig. 6b), and the recorded data provided crucial information on the stability of the base of the T16 support tower. Figure 5 indicates that the groundwater level of the study area is stable and almost constant. The recorded data from the inclinometer and load cell between 2015 and 2020 are discussed below.

- Slope deformation recorded: Three inclinometers were installed on the slope profile, SIS-01, above the landslide area; SIS-03, within the landslide area; and SIS-05, below the landslide area (Fig. 6a). The monitoring depths of these inclinometers range between 20 and 30 m. The recorded data indicated that the maximum relative displacement in the A–A' section did not exceed 1 cm (Fig. 7a). Furthermore, the maximum relative displacement in the B–B' section did not exceed 2 cm (Fig. 7b), and the data did not indicate the existence of a sliding surface, confirming the stability of the landslide area after remediation.
- Anchor load recorded: In total, 12 load cells were mounted on the anchored slope beneath the T16 support tower. As shown in Fig. 8, most load cells could record data without interruption, although their readings were occasionally unstable due to environmental temperature changes (Cheng et al. 2022). Meanwhile, the recorded data indicated that the long-term load ranged between 0.9 T_w and 1.2 T_w (36–48 tons). According to the Taiwan freeway asset management handbook (MOTC 2018), the residual load level was grade D, indicating that the ground anchors were in good condition (Liao et al. 2019). However, some abnormal load cell readings were identified. The LD-01 load cell exhibited a continual decrease in load, and its residual load was less than 0.5 T_w in 2020, indicating a grade B ground anchor. The LD-11 load cell exhibited anomalies in its records. The LD-05 and LD-06 load cells were damaged in 2015 and 2016, respectively, and could not precisely record data during these years. The information above indicates that as much as 33% (4 out of 12) of the load cells did not function properly, reducing the reliability of the monitoring results.

Observational monitoring

The recorded data from the load cell and inclinometer indicated that the landslide area below the T16 support tower remained stable after remediation. However, the reliability of the load cell monitoring data was not ideal. Therefore, this study selected one anchor each (namely, O-19, K-18, G-18, and C-18) from the area adjacent to LD-02, LD-05, LD-08, and LD-11 in the central profile of the anchored slope to perform lift-off tests for verifying the reliability of the monitored data (Fig. 6b). The verification was conducted in September 2020. The results presented in Table 2 indicate that the readings of all load cells, except for the LD-05 load cell, which was damaged, exhibited a relative error of 11%–40% (relative error $= \left(\frac{T_{\text{load cell}} - T_r}{T_r} \right) \times 100\%$) compared to the results of the corresponding lift-off tests conducted on the anchors adjacent to these cells. Additionally, the lift-off load did not reflect the stability suggested by the load cell monitoring results; instead, a clear load loss of approximately 2.3–13.7 tons (about 6%–34% T_w) was observed compared with the design load (T_w).

While the monitoring record of slope deformation confirmed that the slope did not exhibit slippage after remediation, the

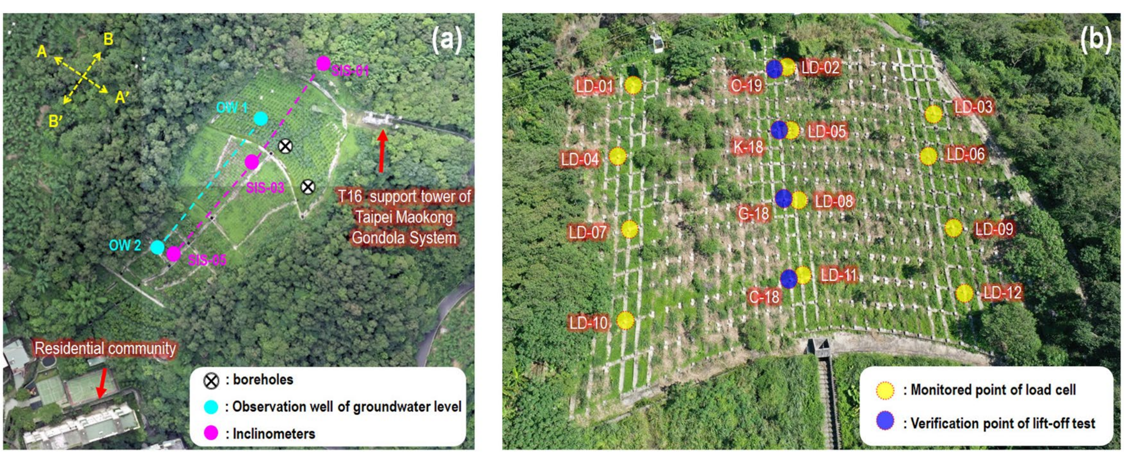


Fig. 6 Distribution of monitoring devices on the remediation slope: **a** locations of boreholes, groundwater observation wells, and inclinometers and **b** locations of the load cells and locations for lift-off testing

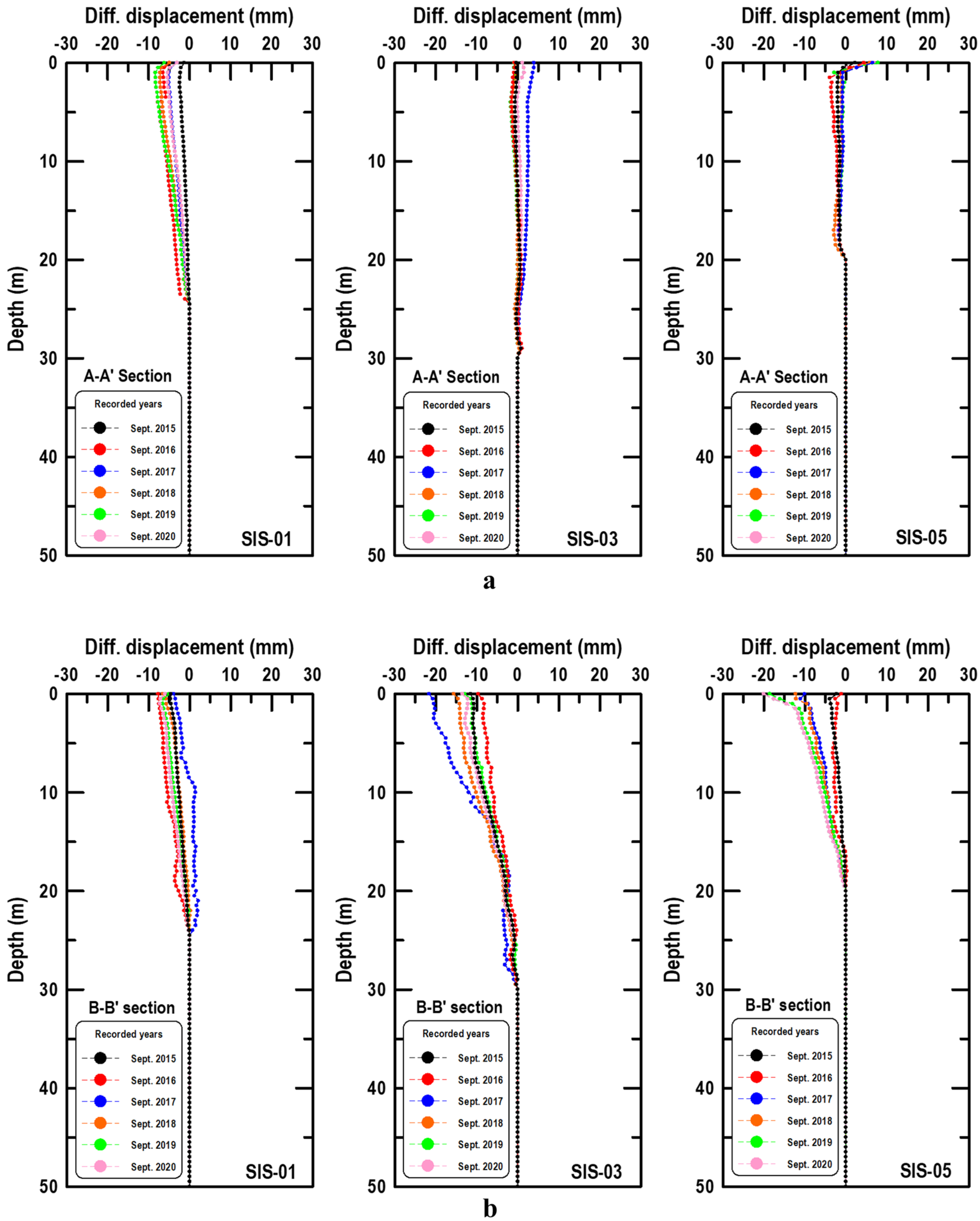


Fig. 7 **a** Slope displacements recorded from the inclinations between September 2015 and September 2020 (A–A′ section). **b** Slope displacements recorded from the inclinations between September 2015 and September 2020 (B–B′ section)

reliability of the monitored anchor load was questionable. The results of limited lift-off tests revealed a clear load loss in the reinforcing anchors on the slope. Therefore, the safety status of the studied slope should be carefully investigated by performing functional inspections and residual load investigations with larger samples. This will help assess the functional grading of the anchored slope, identify the causes and amount of load loss, and, if necessary, suggest rehabilitation measures for the anchored slope, such as corrosion protection or restressing of the ground anchors.

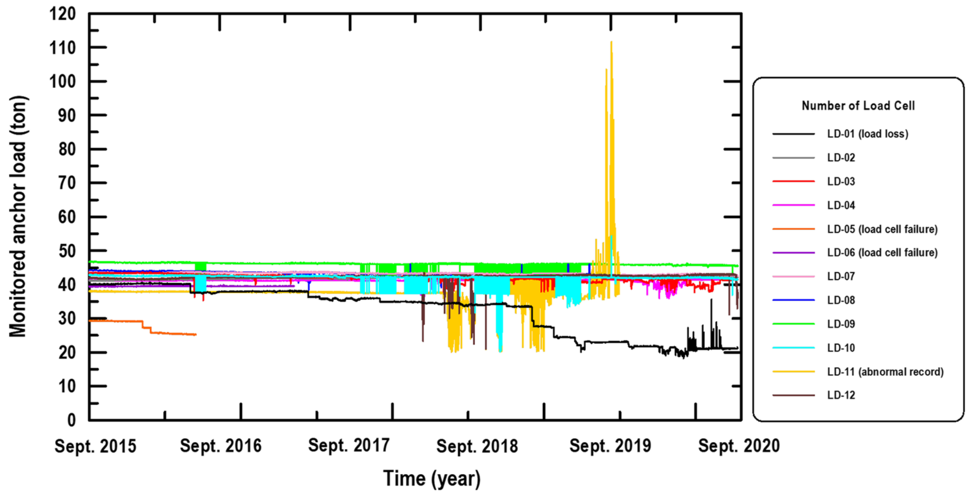


Fig. 8 Long-term loads recorded from the load cells between September 2015 and September 2020

Function inspection, anchoring condition evaluation, and restressing of existing anchors

To determine necessary rehabilitation measures, an investigation was necessary to understand the cause, functional grade, and distribution of load loss on the anchored slope beneath the T16 support tower. Accordingly, this study divided the tasks into two stages: function inspection and rehabilitation operations for the existing 619 anchors. In stage 1, a functional inspection was performed on representative samples (45 anchors) to investigate the functional grading of the existing anchors and determine the cause and distribution of load loss. Based on the stage 1 inspection results and the assessment of the impact of load loss on anchored slope stability, stage 2 involved modified lift-off tests. These tests were conducted comprehensively on the entire slope to investigate the residual loads of the existing anchors, evaluate the anchoring condition, and restress anchor loads up to the design load if necessary.

Inspection of existing anchors

Ensure that the inspection results are representative of all existing anchors on the anchored slope. Following the guidelines of the Taiwan Freeway Asset Management Handbook (MOTC 2018), this study selected 45 anchors out of the total 619 (7.3% of the total number of slope anchors) for functional inspection. As depicted in Fig. 9 (Appendix Table 4 displays the grade of every inspected step and residual load of the inspected anchors), the 45 inspected anchors were distributed across six inspection zones (A1, A2, B1, B2, C1, and C2). Each anchor was subjected to four inspected steps. Step 1 involved visually inspecting the protection cap of the anchor. Step 2 involved inspecting the steel strands and wedges on the anchorage head. Step 3 involved using a borescope to inspect the condition of the steel strands below the anchorage head. Finally, step 4 involved a lift-off test to determine the residual anchor load. Details regarding scores, items, reference photographs, and the weighting or grading for each inspection step are suggested by Liao et al. (2019). Figure 9 also summarizes the identified grades in different colors for each inspected step. The results obtained in each inspected step are described below.

Step 1: visual inspection of the protection cap of the anchor. The protection of the anchor head was a concrete cap. In visual inspections, the majority of the 45 inspected anchors showed no damage or corrosive groundwater flow, with 43 anchors belonging to grades C and D (approximately 95% of the inspected samples). For the remaining 2 anchors, namely, anchor nos. 19 and 21, the protection cap was separated by ≥ 2 mm from the bearing plate; hence, these anchors were classified into grade A (Fig. 9).

Table 2 The relative error between the residual loads recorded from a load cell and those determined from a lift-off test

No. of load cell	Recorded load at the end of Sept. 2020 ($T_{load\ cell}$)	No. of anchor for verifying lift-off test	Lift-off load (T_r)	Relative error, $\left(\frac{T_{load\ cell}-T_r}{T_r}\right)\times 100\%$
LD-02	42.12 T	O-19	37.7 T	11.7%
LD-05	–	K-18	37.4 T	–
LD-08	42.53 T	G-18	32.5 T	30.9%
LD-11	36.88 T	C-18	26.3 T	40.2%

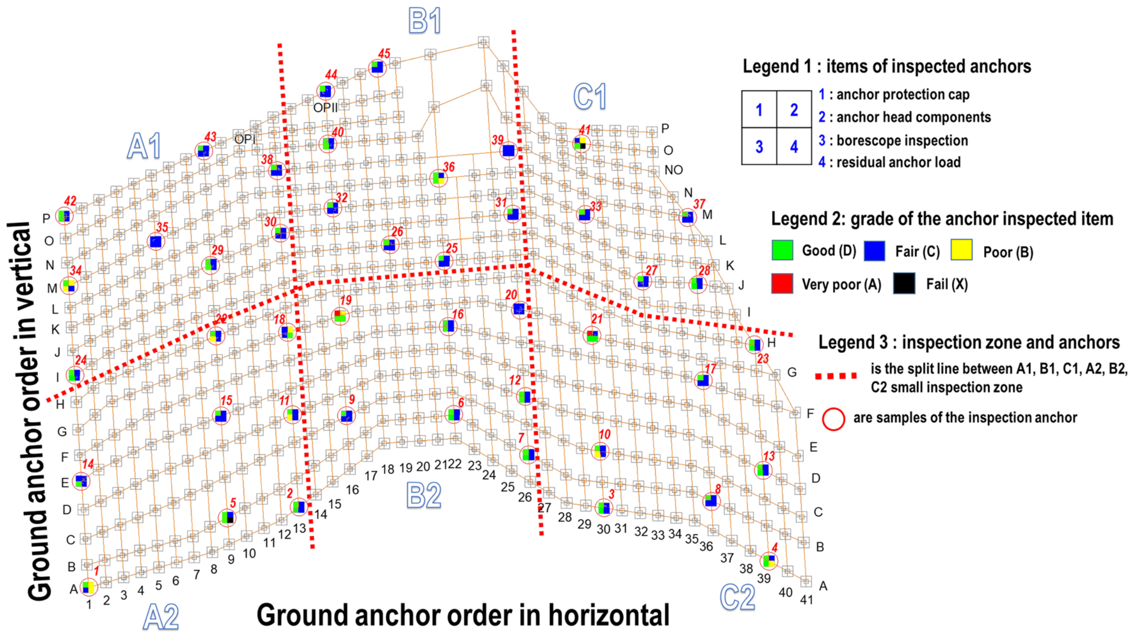


Fig. 9 Layout of the anchors selected for function inspection and the grading results for each step on the inspected anchors

Step 2: inspection of steel strands and wedges on the anchorage head.

The steel strands and wedge components at the anchorage head were investigated after breaking the concrete protection cap. These investigations revealed that 40 (89% of all inspected anchors) belonged to grade C. The remaining 5 anchors (anchor nos. 1, 18, 19, 34, and 41) exhibited corrosion areas exceeding 50% of the surface area of the steel strands or anchorage head; thus, they were classified as grade B (Fig. 9).

Step 3: use a borescope to inspect the condition of the steel strands below the anchorage head.

The slope anchors were installed for permanent corrosion protection. The free length of each strand was covered with a polyethylene tube and filled with grease to prevent corrosion. Anticorrosion quality was verified through a borescope inspection; 41 (91% of all inspected anchors) were classified as grade C or D in step 3. For the remaining four inspected anchors (anchor nos. 10, 11, 22, and 34), rust texture was observed on the strand surface, and the corrosion areas covered approximating 50%–90% of the strand surface; thus, these anchors were classified as grade B (Fig. 9).

Step 4: lift-off test to determine the residual anchor load.

Investigated anchors nos. 1, 4, and 36 had residual loads that exceeded 0.2 T_w but were less than 0.5 T_w; thus, these anchors were classified as grade B. Anchor nos. 5 and 41 were classified as grade X because they were pulled out during the lift-off test. The remaining 40 investigated anchors (89% of all the inspected anchors) were classified as grade C or D. These anchors exhibited a marked load loss of approximately 8–20 tons (0.2–0.5 T_w), with 0.5 $T_w < T_r \leq 0.8\ T_w$ (Fig. 9).

In summary, the inspection of the anchors indicated they were minimally affected by corrosion, attributed to the permanent corrosion protection administered during anchor installation. However, they exhibited a marked load loss, evenly distributed on the anchored slope.

Anchor inspection results

The function inspection results of the selected anchors, presented in Fig. 9 and Appendix Table 4, determine the grading for each divided zone. The total score of the inspected anchors in each zone is divided by the number of inspected anchors to obtain the score and grade. As shown in Table 3, the anchored slope beneath the T16 support tower can be classified as grade C or D (fair or good) based on the current slope conditions. This result is consistent with the slope stability monitoring records described above.

Steps 1–3 of the anchor inspection plan involve subjective and qualitative observations. Quantitative values can provided only through lift-off tests in step 4. However, qualitative and quantitative correlation analyses can be performed for each inspected anchor using a radar chart (i.e., the larger the enclosed area on the radar chart, the better the condition of the anchor). Figure 10 illustrates this (taking anchor nos. 6, 16, 25, and 36 as examples), where almost all inspected anchors had consistent enclosed spaces. However, clear gaps are observed in the residual anchor load directions on the radar charts, indicating that despite the overall slope being stable, the existing anchors exhibited consistent functioning but with compromised residual load performance (load loss).

As mentioned earlier, corrosion can be excluded as the cause of the load loss in the existing anchors. However, determining whether the load loss is associated with the creep of the ground anchor system requires an evaluation of the anchoring conditions through a modified lift-off test. Construction and environmental factors, such as the differential settlement between the slope surface and

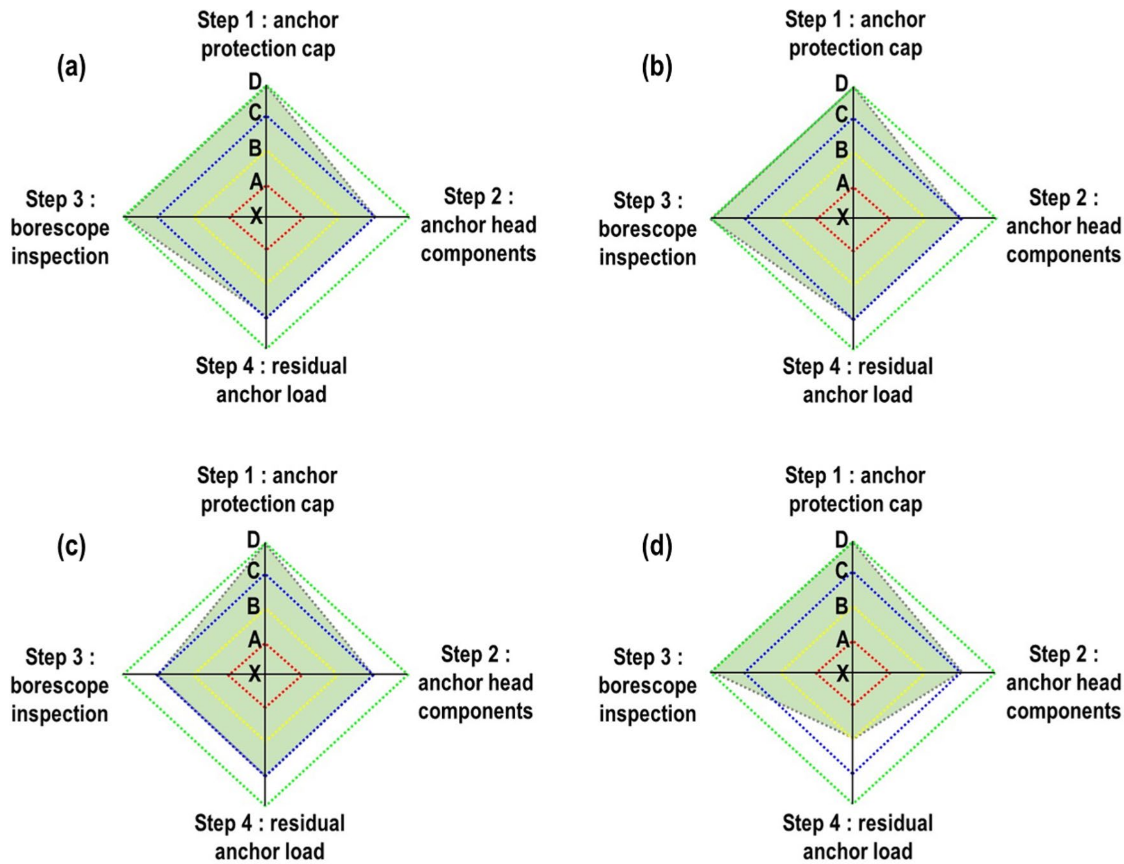


Fig. 10 Radar charts of the inspected anchors: **a** inspected anchor B-22 (anchor no. 6), **b** inspected anchor F-22 (anchor no. 16), **c** inspected anchor I-22 (anchor no. 25), **d** inspected anchor M-22 (anchor no. 36)

tieback structure, were investigated in stage 1. As depicted in Fig. 5, the concrete grid beam structure was supported by a thin layer of residual soil. Following the stress applied to the anchors, the slope surface may experience compression, leading to settlement in the residual layer and causing load loss in the anchors. Based on the aforementioned inference, this study confirmed the geological distribution in the area using records from two boreholes located at the lower right of the anchored slope along the anchor installation angle (Fig. 6a). The two boreholes, each with a length of 24 m, closely matched the length of the slope anchors. The initial 0–4 m of core samples consisted of residual soil, while the subsequent segments (4–24 m) comprised sandstone and alternating sandstone

Table 3 Grading based on the function inspection results for the entire anchored slope and each divide zone

Divide zone	Number of inspected anchors	Sample percentage (%)	T_r (average)	T_r/T_w (average)	Overall score (α)	Grading of anchored slopes
A1	8	7.55%	29.0	0.72	79.81	C
A2	8	7.69%	24.1	0.59	66.83	C
B1	9	8.82%	25.5	0.63	78.49	C
B2	7	6.73%	27.3	0.67	82.50	D
C1	5	5.81%	22.0	0.54	63.50	C
C2	8	6.84%	25.9	0.64	82.02	D
Total (entire zone)	45	7.27%	26	0.64	76.24	C

$\alpha = \sum$ total score of inspected anchors/number of inspected anchors

Grade of the anchored slope: A, very poor; B, poor; C, fair; D, good

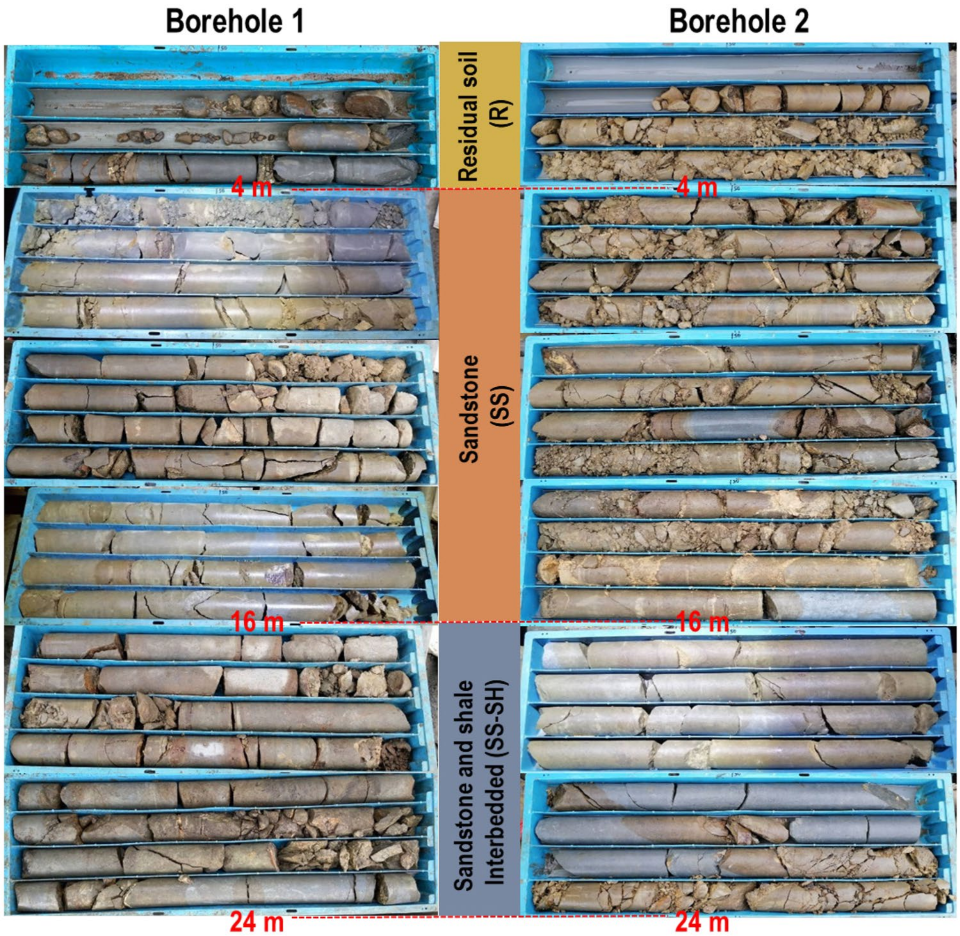


Fig. 11 Boreholes with rock samples obtained from the anchored slope

and shale layers (Fig. 11). This result supports the validity of the earlier inference that identified the residual layer as the cause of the compression and settlement observed in the concrete grid beam.

Fig. 12 Gaps between the concrete grid beam and the ground surface observed from the anchored slope (1–2 cm)

This conclusion is further substantiated by the presence of a 1–2 cm gap observed between the concrete grid beam and the surface soil on the slope (Fig. 12).

Evaluation of anchored slope stability

Results from the functional inspection conducted on the 45 selected anchors revealed an average load loss of 0.34 T_w (Table 3 and Appendix Table 4). Discussing load loss in stressed anchors and its impact on slope stability is essential. However, assessing anchored slope stability amid loading changes on ground anchors is intricately linked to the force equilibrium of the slope. The stress–strain behavior of material properties can be disregarded at this stage. Consequently, the impact of anchors with load loss on the stability of the study case was assessed using the limit equilibrium method (LEM) based on Bishop's simplified method (1955), employing Plaxis 2D LE. As illustrated in Fig. 9, the centerline of the entire slope (profile of anchor nos. 6, 16, 25, and 36) was chosen as representative slices for discretizing the soil mass and determining the factor of safety (FS).

Referring to the slope prototype in Fig. 5, the geological properties (strength parameters) mentioned in the R, SH, SS, and

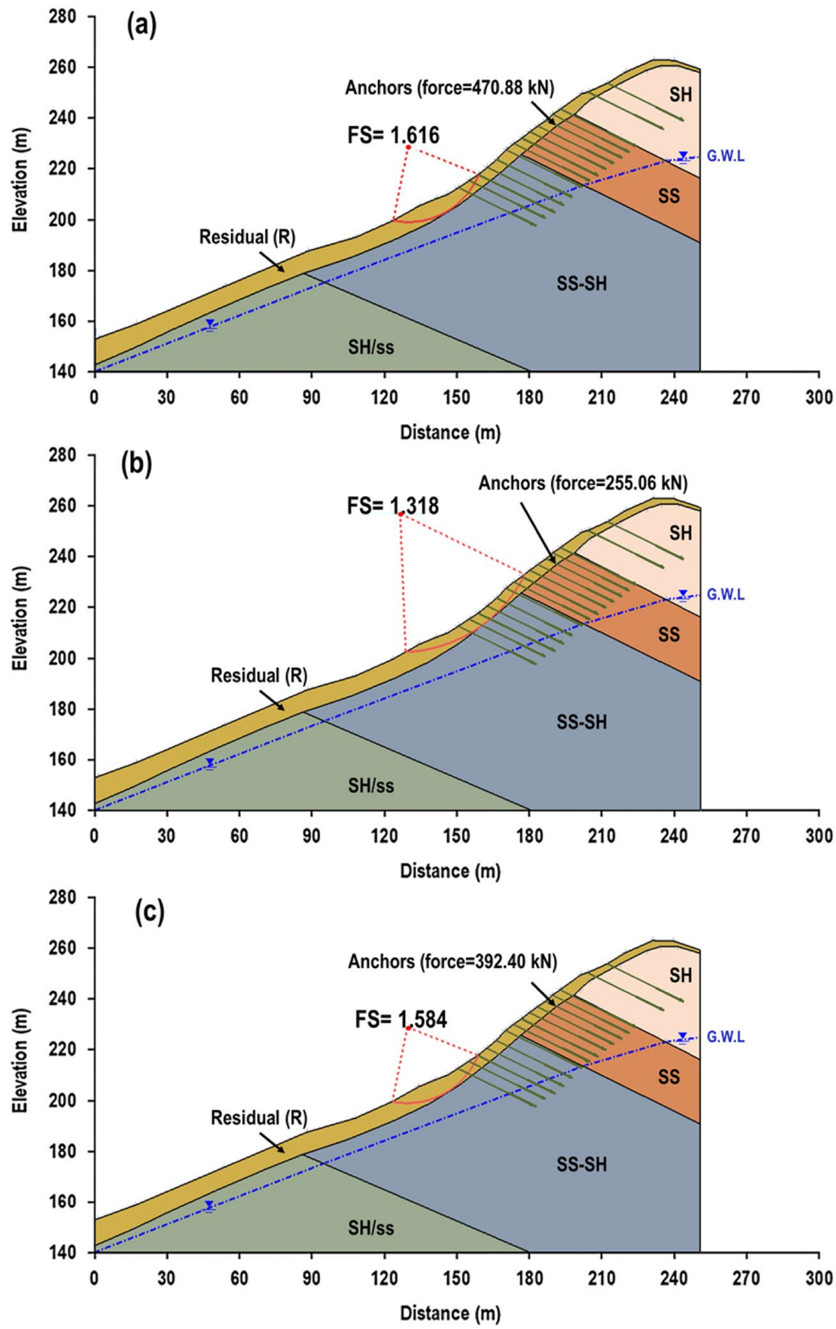


Fig. 13 Results for the FS and critical slip surface of the stability LEM analysis for an anchored slope under different loading conditions: **a** initial stressing condition (T_0=1.2 T_w, =48 tons); **b** load loss condition (T_r=0.64; T_w, =26 tons); **c** restressing load to design load (T_w=40 tons)

SS–SH or SH/ss layers were incorporated to construct the LEM analysis model. The calculated results for FS and the critical slip surface under initial stressing conditions (T_o = 1.2 T_w, = 48 tons) and load loss conditions (T_r = 26 tons) are presented in Fig. 13a, b, respectively. Utilizing the recommended minimum FS values from Duncan and Wright (2005), an FS value of 1.5 signifies slope stability under design requirements. When the average load loss of anchors is below 0.36 T_w (T_r = 0.64 T_w, = 26 tons), FS < 1.5 indicates that the stability of the studied case is lower than the required design criteria. To showcase the contribution of the modified lift-off test in maintaining anchor functionality on the anchored slope, Fig. 13c demonstrates that the average load of ground anchors was restressed to reach T_w (40 tons), resulting in a calculated FS = 1.584, surpassing the stability threshold of FS = 1.5. It indicates the feasibility of the proposed measure for restressing the existing anchors when loading losses.

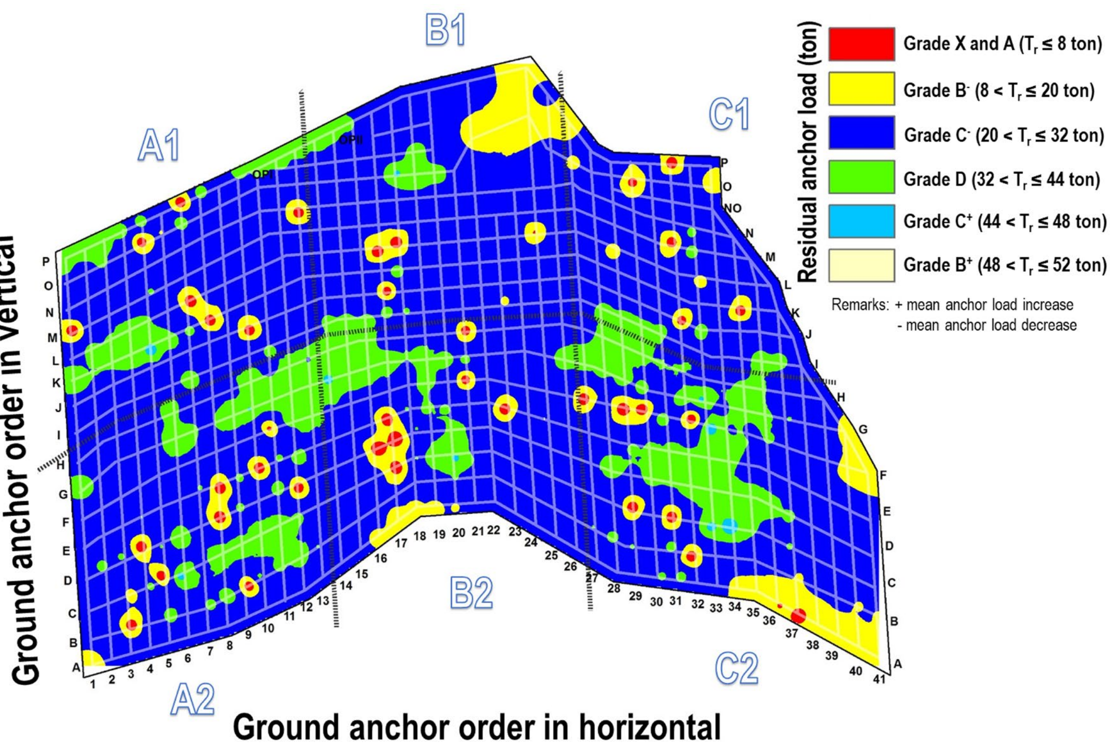


Fig. 14 Distribution of the residual load for all ground anchors in the anchored slope

Residual anchor load distribution and evaluation of the anchoring condition

The results of an in situ observation suggested that the anchors were not damaged by corrosion; however, a general load loss occurred due to compression settlement between the concrete grid beam and the residual soil layer. To formulate proactive measures to maintain the functioning of the anchors on the anchored slope, this study used a modified lift-off test to investigate the residual load and evaluate the anchoring conditions of all existing anchors on the anchored slope. This also involved excluding whether the anchor load loss was caused by the creep of the ground anchor system and assessing the feasibility of restressing the existing anchors.

Figure 14 displays the distribution of all the residual anchor loads in the anchored slope. The residual load level was classified as grade C, and most of the residual loads were ranging from 20 to 32 tons, and the load loss being approximately 8–20 tons (0.2–0.5 T_w). This result is consistent with the previous functional inspection results. The figure also indicates that about 7% (41 out of 574 anchors) of the anchors might fail (grades A and X) during the modified lift-off test. Typically, when the modified lift-off test is carefully executed, the failure ratio may vary based on the construction quality of the ground anchors, their service life, and the influence of the surrounding environment.

In addition to the residual anchor load, the anchoring condition of each anchor can be evaluated during the modified lift-off test. After obtaining the residual load of each anchor, the $k_{s(L)}$ that must be achieved under maximum lift-off load (T_L) can be calculated using Eq. (2). Figure 15 shows the distribution of the $k_{s(L)}$ that must be achieved for all anchors. Figure 16 shows the distribution of the $k_{s(10)}$ calculated following Eq. (1) by using the measured deformation of the anchorage head when the maximum lift-off load (T_L) was maintained for 10 min during the modified lift-off test. When the $k_{s(L)}$ was greater than the $k_{s(10)}$, the anchoring conditions for all anchors were satisfactory; thus, the creep of the ground anchor system was not the cause of anchor load loss. The obtained data indicate that all inspected anchors satisfy the above condition ($k_{s(L)} > (k_{s(10)})$. The evaluation results suggest that the load loss was not caused by either anchor corrosion or creep. Instead, it was attributed to compression settlement between the concrete grid beam and the residual soil layer. Furthermore, the load cell data recorded between 2015 and 2020 (Fig. 8) suggests that the anchor load remains constant, as evidenced by the consistent loading trend observed during that period. Therefore, it can be inferred that compression settlement due to construction results in anchor load loss, which may occur suddenly after the tieback anchor was installed and stressed in the year 2010. Engineers could restore the load loss through restressing without necessarily installing additional anchors, thereby saving construction time and costs.

Restressing the existing anchors

As mentioned above, the anchored slope beneath the T16 support tower showed no signs of instability, as confirmed by slope stability monitoring. Further investigations revealed that nearly all the anchors experienced a load loss ranging from 8 to 20 tons.

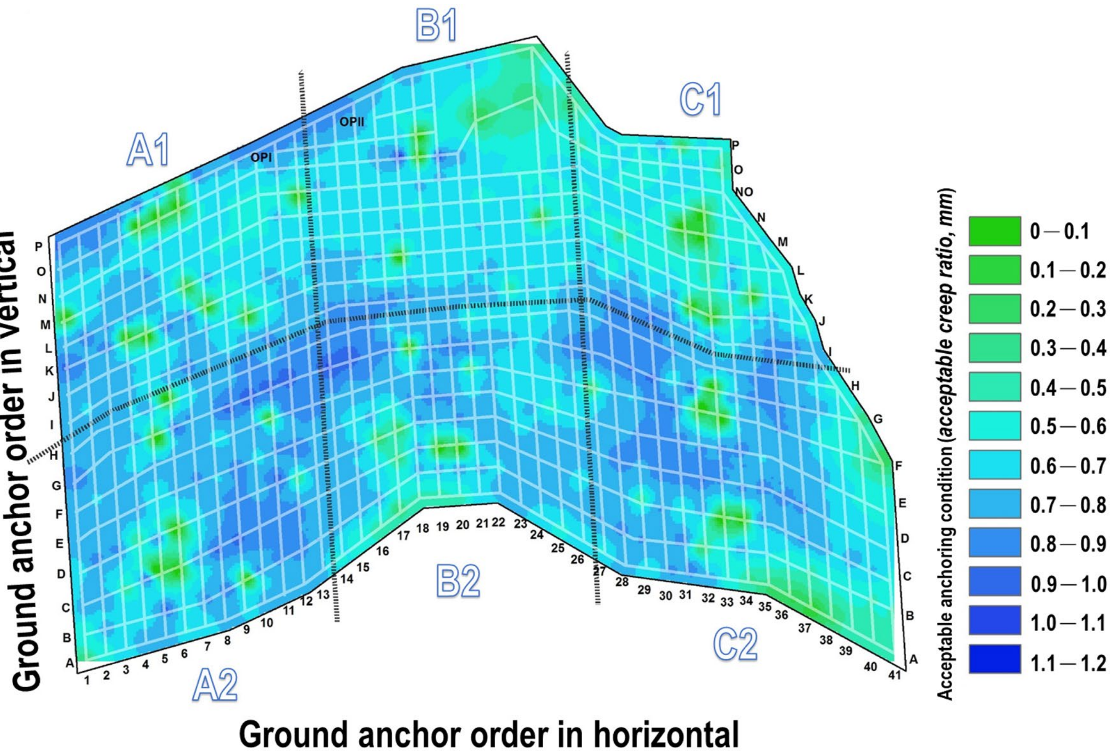


Fig. 15 Distribution contours of acceptable creep ratio ($k_{s(L)}$) (calculated using Eq. (2)) for all ground anchors in the anchored slope

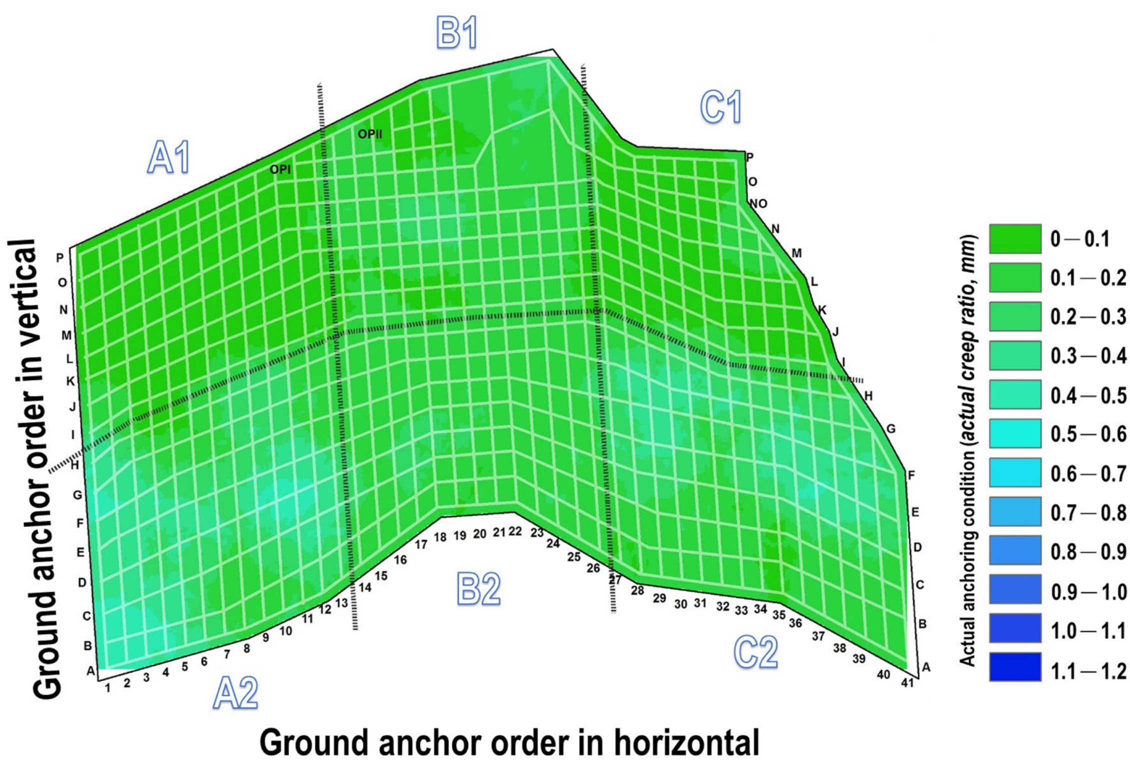


Fig. 16 Distribution contours of actual creep ratio ($k_{s(10)}$) (calculated using Eq. (1)) for all ground anchors in the anchored slope

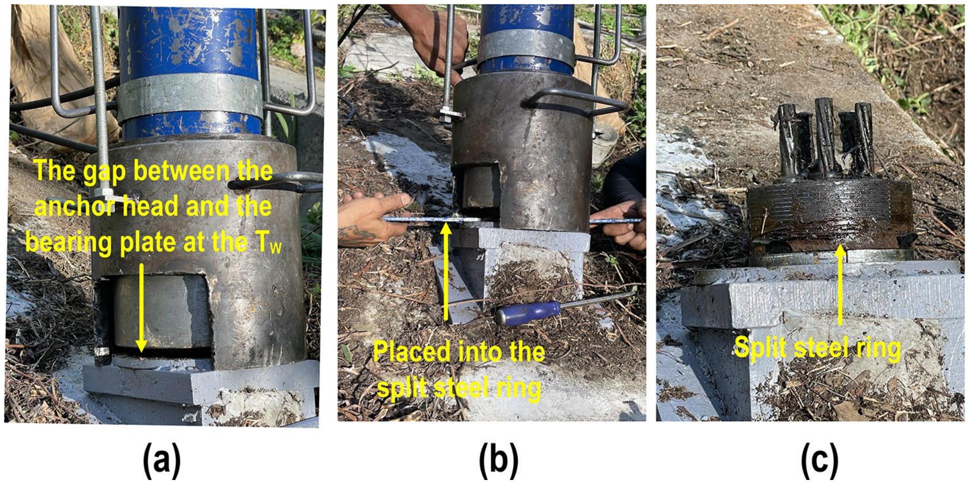


Fig. 17 Photos of the restressing procedure performed in the modified lift-off test: **a** the gap between the anchor head and bearing plate at the design load, **b** holding the anchor head at the design load and placing a steel split ring in the gap between the anchor head and the bearing plate, and **c** removing the lift-off load from the anchor head and completing the restressing process

Based on the results of slope stability analyses under different conditions for the slope, to ensure the anchored slope stability beneath the T16 tower and safeguard the residential community downhill, it is suggested that the load of the anchors experiencing load loss should be increased to the designed load (T_w) through restressing to maintain the design performance. The existing anchors underwent the modified lift-off test to investigate their residual loads, evaluate their anchoring conditions, and synchronize to achieve the restressing. Similar to Fig. 3, when increasing the load to the design load (T_w), a split steel ring of appropriate thickness must be placed into the gap between the anchor head and the bearing plate by using simple tools to achieve restressing (Fig. 17). Because the load to be increased for each anchor is different, the size of the gap between the anchor head and the bearing plate is not fixed. Therefore, split steel rings with thicknesses of 3, 5, and 10 mm (Fig. 18) were used to provide flexibility in the restressing procedure. In this case, a split steel ring with a thickness of approximately 1.5 mm is required to increase the load by 1 ton {= [$\triangle P$ (load charge) × L_{eff} (effective free-strand length)] / [E (Young's modulus of the steel strands) × A (cross-sectional area of all the engaged steel strands)] = (1000 kg × 15,000 mm) /(2×10^6 kg/cm^2 × 4.9355 cm^2)}.

Figure 19 displays the load distribution of all anchors on the anchored slope after performing the modified lift-off test (restressing procedure). It indicates that the loads of most anchors were restored to the design load level (grade D). However, as stated above, during the implementation of the modified lift-off test, approximately 7% of the anchors might fail due to phenomena such as the broken failure of strands and the pull-out occurring at the fixed end. These anchor failures mostly occurred when investigating the residual load and not during the restressing stage, and this study adopted a principle of one-to-one reinforcement for each failure to restore the original design performances. There are 43 reinforced anchors installed on the anchored slope (2 and 41 anchors were reinforced because of failures found during stages 1 and 2 of the investigation, respectively). Figure 20 depicts the load distribution of the anchored slope after reinforcing the anchors; all the anchors were rehabilitated to the design load (T_w) of 40 tons.

Advantages of the adopted measures

In past design and construction practices, when anchor load loss is identified on an anchored slope, the typical remedial measure is to restore the initial design performance by adding additional

Fig. 18 Photos of split steel rings with different thicknesses that were used in this study

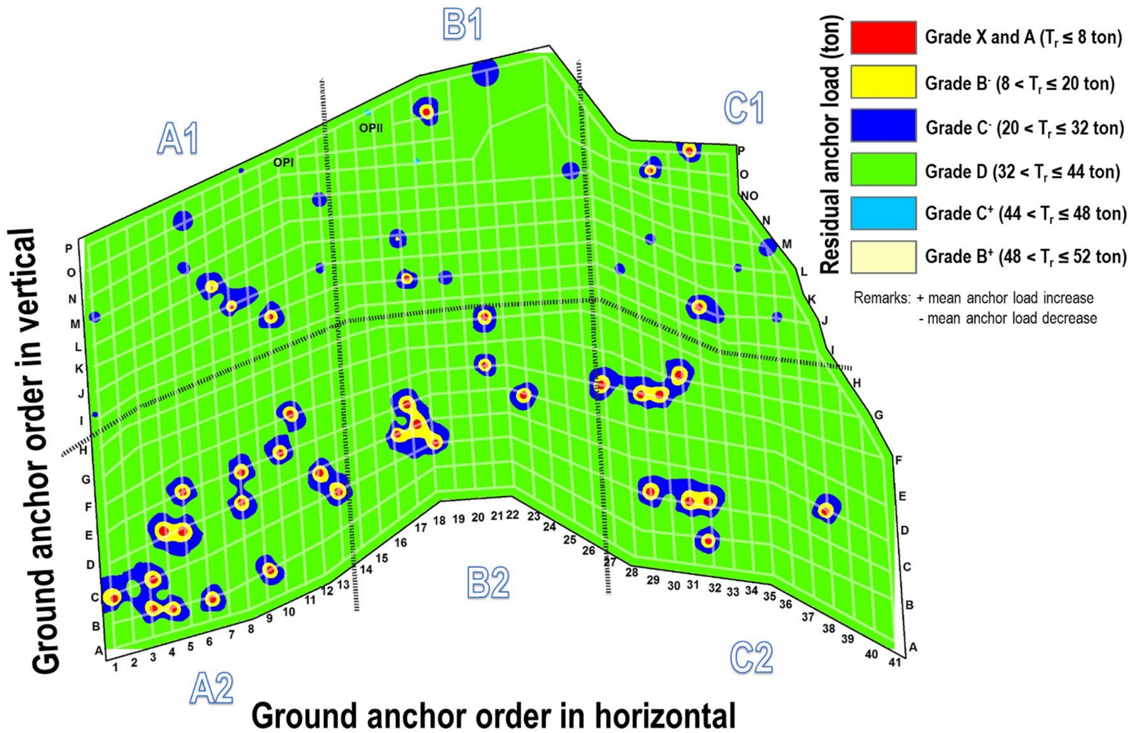


Fig. 19 Load distribution on the anchored slope after performing restressing in the modified lift-off test

structural reinforcement. In the case study of this paper, the investigated data presented in Table 3 indicate that the average anchor load loss of the anchored slope is approximately 36% of T_w. If tieback anchors are adopted to restore the load loss to the initial design condition, 223 ($619 \times 0.36 = 223$) extra anchors need to be installed. In this study, we successfully rehabilitated the anchored

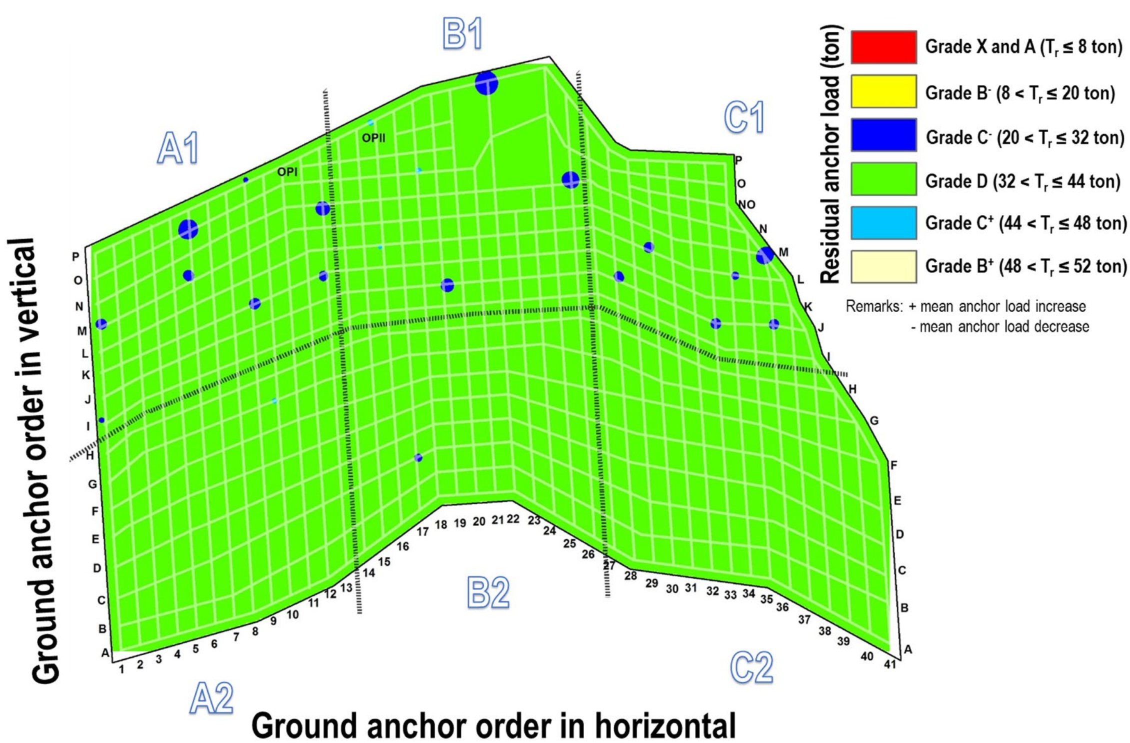


Fig. 20 Load distribution on the anchored slope after reinforcing failed ground anchors

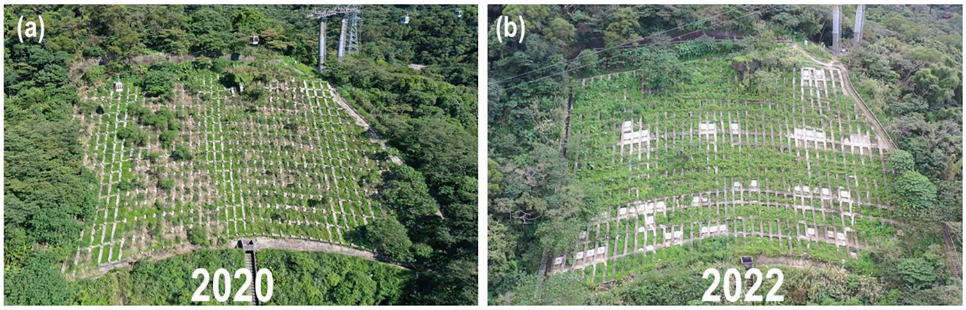


Fig. 21 Comparison of the anchored slope before and after restressing: **a** before restressing in 2020 and **b** after performing restressing in the modified lift-off test in 2022

slope to the initial design condition by adopting modified lift-off tests. Although 43 anchors had to be reinforced, this number is only approximately one-fifth the number of anchors that must be installed in a conventional approach; this result highlights the advantages of the modified lift-off test for restressing in terms of reducing construction time and costs. Moreover, as displayed in Fig. 21, the measures adopted in this study did not add a substantially higher number of concrete structures to the original anchored slope; thus, these measures are environmentally friendly and contribute to sustainable development.

Conclusions

In this study, a modified lift-off test is proposed, which utilizes the same equipment and involves processes similar to the typical lift-off test. The applicability of this proposed method for inspecting the performance of existing anchors and rehabilitating load loss anchors has been demonstrated through a case study of a rehabilitated landslide-anchored slope. The following conclusions can be drawn from the findings of this study:

- The proposed modified lift-off test enables the investigation of residual anchor load, evaluation of anchoring conditions (anchored capacity or creep ratio), and implementation of the restressing function for existing anchors. This method does not require dedicated equipment and does not alter the engaged position of the lock-in wedges on steel strands, thereby avoiding any potential danger to weak areas prone to corrosion on the steel strands of existing anchors.
- Observations from the case study indicate that load loss might occur on an anchored slope even when no excessive deformation is recorded, anchor corrosion is not notable, and the creep ratio of the ground anchor system is not high. Instead, load loss might occur because of the residual soil where the tieback anchor structure is located. In the case study, an average load loss of approximately 36% occurred compared to the design load.
- This study conducted a two-stage procedure that simultaneously facilitated the investigation and rehabilitation of an anchored slope with load loss. In stage 1, the study performed functional inspections for a representative sample of anchors to determine the cause, level, and distribution of load loss. In stage 2, a modified lift-off test was adopted to conduct a residual load investigation for all slope anchors in the study area, evaluating the anchoring condition and restressing the anchor to the initial design load when necessary.
- Implementing the modified lift-off test might cause some anchors to fail (e.g., pull-out or broken failure). This study's fail rate was approximately 7% (43 out of 619 anchors). These failed anchors had to be replaced by installing extra anchors to restore the initial design performance. In traditional design and construction practices, about 223 additional anchors were required in the study area. However, the proposed method only necessitates approximately one-fifth of the anchors compared to the conventional approach. This result underscores the advantages of restressing through the modified lift-off test in reducing construction time and costs.
- The rehabilitation measures adopted in this study involve adding limited concrete structures to the original anchored slope; thus, these measures are environmentally friendly and suitable for sustainable development.

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Data availability

Data is available on request from the authors.

Declarations

Conflict of interest The authors declare no competing interests.

Appendix

Table 4 Grade of every inspected step, residual load, total score, and overall grade of the inspected anchors

Inspected anchor	No. of anchor	Step 1: anchor protection cap	Step 2: anchor head components	Step 3: borescope inspection	Step 4: residual anchor load	T_r	T_r/T_w	Total score of inspected anchor (β)	Grade of anchor
1	A-01	D	B	C	B	13	0.32	70	C
2	A-13	D	C	D	C	25	0.63	85	D
3	A-30	D	C	D	C	32	0.80	85	D
4	A-39	D	C	D	B	18	0.46	81	D
5	B-09	D	C	D	X	0	0.00	0	X
6	B-22	D	C	D	C	25	0.63	85	D
7	B-26	D	C	D	C	28	0.70	85	D
8	B-36	D	C	C	C	21	0.53	78	C
9	C-16	D	C	C	C	21	0.52	78	C
10	C-30	D	C	B	C	30	0.75	69	C
11	D-13	D	C	B	C	27	0.66	69	C
12	D-26	D	C	D	C	29	0.73	85	D
13	D-39	D	C	D	C	22	0.55	85	D
14	E-01	C	C	D	C	30	0.75	83	D
15	E-09	D	C	C	C	30	0.75	78	C
16	F-22	D	C	D	C	27	0.67	85	D
17	F-36	D	C	D	C	29	0.73	85	D
18	G-13	C	B	C	D	37	0.92	83	D
19	G-16	A	B	D	D	37	0.93	85	D
20	G-26	C	C	C	C	31	0.78	75	C
21	G-30	A	C	D	D	32	0.81	89	D
22	H-09	D	C	B	C	27	0.67	69	C
23	H-39	D	C	D	C	20	0.51	85	D
24	I-01	D	C	D	C	31	0.78	85	D
25	I-22	D	C	C	C	23	0.57	78	C
26	J-19	D	C	C	C	24	0.61	78	C
27	J-33	D	C	C	C	28	0.71	78	C
28	J-36	D	C	D	C	27	0.68	85	D
29	K-09	D	C	D	C	26	0.65	85	D
30	K-13	D	C	C	C	27	0.68	78	C
31	K-26	D	C	C	C	27	0.66	78	C
32	L-16	D	C	C	C	26	0.70	78	C
33	L-30	D	C	C	C	28	0.73	78	C
34	M-01	D	B	B	C	29	0.68	65	C

Table 4 (continued)

Inspected anchor	No. of anchor	Step 1: anchor protection cap	Step 2: anchor head components	Step 3: borescope inspection	Step 4: residual anchor load	T_r	T_r/T_w	Total score of inspected anchor (β)	Grade of anchor
35	M-06	C	C	C	C	27	0.48	75	C
36	M-22	D	C	D	B	19	0.62	81	D
37	M-36	D	C	C	C	25	0.62	78	C
38	N-13	D	C	C	C	25	0.63	78	C
39	N-26	C	C	C	C	25	0.56	75	C
40	O-16	D	C	D	C	22	0.00	85	D
41	O-30	C	B	D	X	0	0.80	0	X
42	P-01	D	C	D	D	32	0.78	96	D
43	P-09	D	C	C	C	31	0.77	78	C
44	P-16	D	C	C	C	31	0.71	78	C
45	P-22	D	C	C	C	28	0.68	78	C
Average		C–D	C	C–D	C	26	0.64	76	C-D

β is the total score of the inspected anchor [= (10 × grade of step 1) + (15 × grade of step 2) + (30 × grade of step 3) + (45 × grade step 4)].
Grade of the anchored slope: A, very poor; B, poor; C, fair; D, good

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