Anchors of Anchored Slopes in Taiwan

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ABSTRACT: A catastrophic failure of an anchored cut slope at the national expressway in 2010 uncovered the status quo of tie-back anchors in Taiwan. Serious corrosion of anchor components due to poor corrosion protection was found to be the most obvious factor contributing to this landslide among other factors. After an extensive island-wide investigation on the existing anchored slopes, similar corrosion problem was found in many other anchored slopes. After the investigation, the construction and maintenance practice of anchored slopes had been fundamentally changed in Taiwan. This paper covers the inspection results on anchored slopes and also the measures taken to improve the corrosion protection of existing anchors and new anchors. Based on the problems found from the existing anchored slopes, some modifications on anchor tendon assembly and cement grouting practice had been developed to upgrade the corrosion protection of the new anchors and to monitor the long-term anchor load change as well.

KEYWORDS: Ground anchor, Corrosion, Remedial measures, Anchored slopes

1. INTRODUCTION

A catastrophic dip slope failure occurred suddenly at an anchored cut slope of Taiwan national expressway No. 3 in 2010 after 13 years in service (Figure 1). Originally, this slope was supported with a 20 m high retaining structure with precast RC crosses on slope face and 10 levels of tie-back anchors. Totally, 572 ground anchors were installed with a pre-stressed load of 60 tons each. From the remains of anchors on site, it was found that a large portion of anchors were seriously corroded (Figure 2) due to improper corrosion protection under the anchor head. Since ground anchors with the similar construction practice have been widely used to support the roadside slopes in Taiwan, they are likely to suffer similar corrosion problem (Lee et al., 2013 and Liao et al., 2013). The Ministry of Transportation and Communication (MOTC) of Taiwan government launched an extensive island-wide inspection program on the status quo of existing anchored slopes along the highways, railways and public roads (TGS, 2011 and Liao et al., 2014). Totally, more than 30,000 anchors were inspected and it had been concluded that anchor corrosion was a systematic problem island-wide for anchored slopes. After the investigation, immediate measure was taken to protect the existing anchors from further corrosion. In the meantime, the stability of existing anchored slopes was checked and additional measures were taken to make up the loss of anchor capacity due to corrosion and other causes. For the new anchors being installed to compensate the loss of tie-back capacity of corroded anchors, some modification on anchor tendon assembly and cement grouting process are suggested to upgrade the corrosion protection of the new anchors and to reliably monitor the long-term anchor load change.

Figure 1 Landslide on National Expressway No. 3 in Taiwan (photo taken on April 25, 2010)

2. DISTRIBUTION OF ANCHOR CORROSION ON THE SLOPE

Figure 2 Seriously corroded and broken steel strands found from at the landslide site

During the process of slope sliding, a large number of ground anchors were ripped off by the massive forces generated from the sliding mass. Serious corrosion observed on the ground anchor components indicated the abundance of groundwater in the slope. Figure 3 summarizes the field inspection results of ground anchors. By measuring the length of remained steel strands on the sliding surface, three types of steel strands breakage can be categorized. The "Red" category stands for the anchors of which strand breakage was closely under the anchor head. The "Yellow" category stands for the strand breakage in between anchor head and sliding surface. The "Green" category stands for the strand breakage near the sliding surface. The "Blue" category stands for the anchors remained on the slope face. Since the "Blue" anchors located on the not moving portion of the slope, they had no direct link to the causes of this landslide.

If neglecting the number of anchors still remained on the face slope (Blue category), approximate 40 percent of the broken ground anchors were in Red category. They were all located in the range between 5 - 7m above and 1- 3 m below the outcrop line of sliding surface on the face slope. For anchors located within this range, some showed white stain under the RC cap of anchor from the photos taken prior to the landslide. It is the deposit of calcium carbonate and is the sign of long time groundwater effluent from the anchor hole. As indicated by the distribution of Red marked anchors in Figure 3, the groundwater level could rise to 5 - 7m above the outcrop line on the face slope. When the slope mass slid down, the steel strands of anchors in Red category broke at a location very close to the anchor head. It implies that steel strands were corroded under the anchor head for anchors in the Red category. Above the Red zone was the Yellow zone where steel strands were broken in the free length section and the breakage location was at some distance away from the anchor head. Since no anchor was actually pulled out from its fixed end, it can be concluded that all the failed anchors were resulted by the breaking of steel strands at different locations in free length.

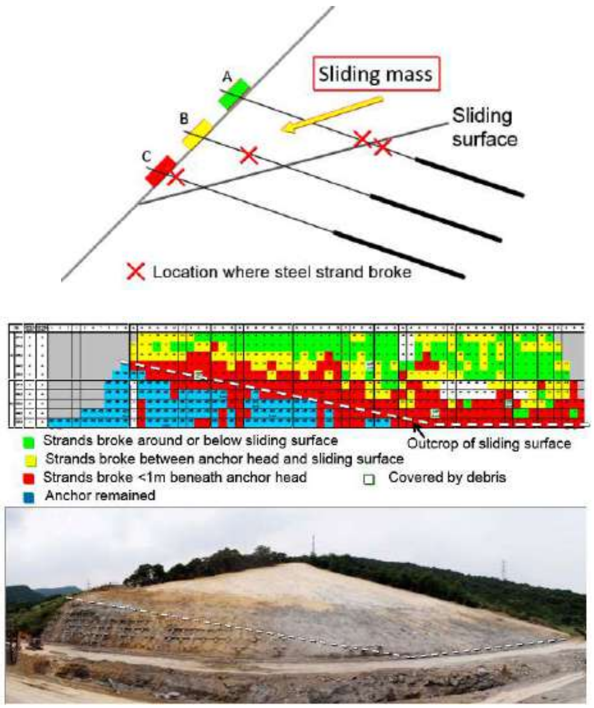

Figure 3 Exposed sliding surface and distribution of anchors with different strands breakage locations on the free anchor end (Liao et al, 2013)

3. STATUS QUO OF ANCHORS AT THE MOMENT OF LANDSLIDE

During anchor construction, it was the standard operation procedure to inject the entire anchor hole with cement grout first and then inserted the tendon assembly to the hole later. In theory, the annular space between anchor hole and plastic sheath of the free anchor end should be fully filled and sealed with cement grout. However, the remains of anchors left on the sliding surface did not show that way (Figure 4). There was ungrouted void both inside and outside of the plastic sheath in free anchor end. Obviously, some cement grout might have leaked out through the cracks and joints inside the slope or it might simply be a result of mal-practiced anchor construction. Not surprisingly, steel strands with improper corrosion protection corroded due to exposure to humid underground environment or being submerged by groundwater.

Figure 5 illustrates the ungrouted void under the anchor head due to improper anchor hole grouting. When anchor is inclined downward, the void and the ungrouted annular space outside the plastic sheath can easily become a storage space for the perched groundwater in slope. Having the perched water in the anchor hole, the unprotected steel strands are constantly exposed to or submerged by groundwater. Not for long, the steel components of anchor become corroded quickly. The corrosion of steel strands can be inspected by the endoscope images taken when inspecting the portion of steel strands under anchor head.

Figure 4 Ungrouted void in free anchor end (inside and outside of plastic sheath) found from anchors left on the sliding surface

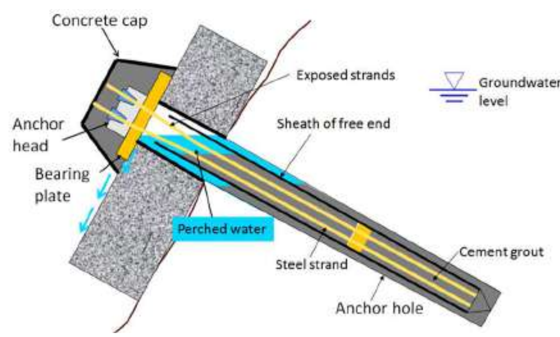

Figure 5 Schematic diagram of ground anchor installed in the slope

Figure 6 shows the endoscopic images taken from the anchors remained on the face slope of the Expressway landslide. In general, all anchors inspected suffered serious strands corrosion problem and should be classified as unacceptable condition according to the BSI standards for ground anchorages (BSI, 1989). Interestingly, the endoscopic images showed some wires of the strand had already broken at the time of endoscope inspection (Anchor III) and some strands were surrounded by weeds inside the anchor hole (Anchor V).

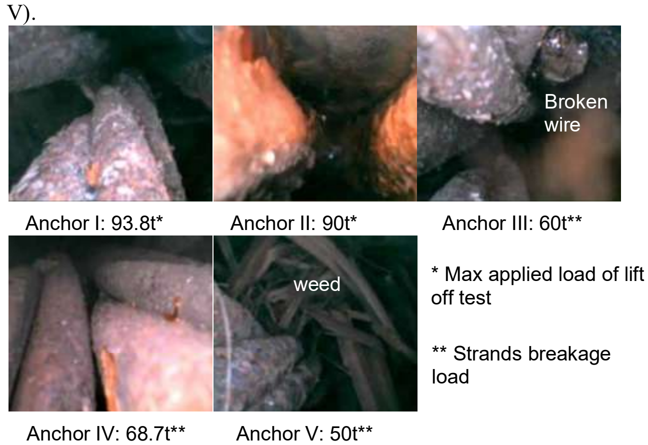

Figure 6 Images of endoscope inspection taken under the anchor head before carrying out the anchor lift off test

Lift off test was carried out on these anchors and the test results, such as lift off load and maximum applied load, are listed in Table 1. Obviously, there is no clear correlation between breakage load and the extent of surficial corrosion of steel strands. For example, the surficial corrosion condition of steel strands of Anchors I & II is no better than Anchors III, IV, and V. But Anchors I & II could sustain the maximum pull-out load about 50% higher than the other three anchors. Anchors I & II showed no strand breakage up to maximum applied load; Anchors III, IV, and V showed strand breakage during stressing and the maximum load applied was lower. For those anchors failed by strands breakage, some wires in the strands (i.e., the strands which are subjected to most serious corrosion or most stressed) broke first during stressing. After that, the load was redistributed to other wires and caused a chain-reaction type of breakage. In other words, strands may be broken in a wire-by-wire pattern; anchors may be broken in a strand-by-strand pattern and then a brittle type of failure occurs on anchor.

Table 1 Lift off test results of five anchors remained on face slope

Anchor No.	Design load (ton)	Lift off load (ton)	Max applied load (ton)
I	60	No lift off	93.8
II	60	88.2	90.0
III	60	54.8	60.0*
IV	60	65.9	68.7*
V	60	43.6	50.0*

4. INSPECTION PROCEDURE OF EXISTING ANCHORS

The following steps have been taken to inspect the existing anchored slopes and evaluate the residual stability of anchored slopes along freeways, major highways and railways all over Taiwan:

(1) **Visually inspect and hammer tapping all the concrete protection cap of anchors (Figure 7):** The integrity of concrete cap can be easily detected by hammer tapping. Special attention should be paid to the cracks on concrete cap and the sign of groundwater leaking out from the concrete cap. If there is a constant water flow from within the anchor hole, calcium carbonate (white stain $CaCO_3$) will deposit under the concrete cap and can be easily spotted.

Figure 7 Visual inspection and hammer tapping on the concrete cap of anchor

(2) **Remove the concrete cap and inspect the steel strands and wedges on the anchor head (Figure 8):** If the integrity of concrete cap is good, normally the appearance of steel strands and wedges also look good. Otherwise, a clear sign of corrosion can be observed on the strands and wedges.

Figure 8 Remove the concrete protection cap of anchor head

(3) **Use endoscope to inspect the condition of steel strands beneath the anchor head (Figure 9):** Usually, the appearance of anchor head components does not necessarily correspond to the extent of corrosion on steel strands beneath the anchor head. So it is necessary to use endoscope to do a close up inspection on the corrosion condition of steel strands under the anchor head.

Figure 9 Use endoscope to inspect steel strands under anchor head

(4) **Carry out the lift off test to determine the residual anchor load (Figure 10):** It is normal to have a residual anchor load varied within ± 20% range of design load. For those anchors suffering serious strands corrosion problem, extra caution must be exercised to avoid breaking the rusty steel strands during lift off test. If the residual anchor load goes beyond 130% of design load, it is an indication of slope displacement. Immediate measures must be taken to resume the stability of slope. If the anchor load falls below 80% of design load, it may be resulted by problems associated with fixed end, free end, and anchor head; or simply a load redistribution of the anchored slope. The real causes should be observed and verified from the timely slope inspection work carried out afterward.

Figure 10 Lift off test for determining the residual anchor load

As shown in Table 2, an example anchor is used to demonstrate the step-by-step process to get scores for the inspected anchors. This example anchor got a score of 70.75 and graded as "Fair" condition (Table 3). But, it suffered severe strands corrosion and its residual load was high and fell between 0.8 to $1.1T_w$. This is the type of anchor which should be treated with extra caution. The high residual anchor load may be an indication of slope displacement which may lead to a sudden failure of anchored slope.

Based on the results of anchor inspection on the selected anchors, the overall safety of an anchored slope can be evaluated by adding up the total scores of all the inspected anchors and divided by the number of inspected anchors. It yielded a value for this particular anchored slope and was used to grade the status of anchored slope (Table 4).

After inspecting tens of thousands ground anchors in Taiwan, it is certain that almost all the anchors installed in Taiwan have suffered various degrees of corrosion. In general, if the ground anchors are below the groundwater surface, anchor corrosion can be severe; where anchors are above the groundwater surface or with no groundwater, anchor corrosion can be minor. However, there is no clear relationship among the findings from each step mentioned above. For example, the visual inspection on the concrete cap of anchor could not unveil the actual corrosion condition of steel strands under the anchor head. In addition, there is also no clear relationship to link the visual inspection results from either concrete cap inspection or endoscope inspection of steel strands to the residual anchor capacity determined from the lift off test. In other words, good exterior condition of concrete cap cannot guarantee no corrosion on the steel strands and/or wedges of the anchors. Minor corrosion on the steel strands observed from endoscope does not mean that the existing anchors can provide good residual load to hold back the slope. Finally, since only 10% of total ground anchors on each slope are normally chosen to carry out the lift off test, there is concern that the test number is under representative, especially when there is a large variation among the residual loads determined from different anchors.

Table 2 Example case of an anchor inspection result

Step	Description	weighting	Score
1	Visual inspection on concrete protection cap	10%	10
2	Inspection on steel strands and wedges on anchor head	15%	11.25
3	Endoscope inspection on steel strands beneath the anchor head	30%	4.5
4	Determine the residual anchor load by lift off test	45%	45
		Total score	70.75

Table 3 Grading of single anchor based on the inspection score (β)

Inspection score	Grade	Remarks
0	X (out of function)	
$\beta \leqq 30$	A (Very poor)	
$30 < \beta \leqq 55$	B (Poor)	
$55 < \beta \leqq 80$	C (Fair)	■
$80 < \beta$	D (Normal)	

Table 4 Grading of an anchored slope based on total scores of all the inspected anchors (α)

Overall total score	Grade	Remarks
$\alpha \leqq 30$	A (Very poor)	
$30 < \alpha \leqq 55$	B (Poor)	
$55 < \alpha \leqq 80$	C (Fair)	
$80 < \alpha$	D (Normal)	
Note: α= total scores of inspected anchors / No. of inspected anchors		

If a majority of anchors on a slope showed an increase in prestressed load. Then it is necessary to study the causes of the anchor load increase and find out the suitable remedial measures to be taken. However, it is not suggested to lower the residual load of overstressed anchors because it may trigger further slope displacement and deteriorate the stability of slope. In fact, if the anchor load of an anchored slope is increasing, it is a clear indication that the original anchor load is unable to provide sufficient tie-back load to hold the slope in place. Under this circumstance, additional anchors may be needed to resume the stability of the slope. But more information about the slope should be collected re-evaluate the stability of slope, including the geological and groundwater conditions of the slope.

On the other hand, if the lift off tests carried out on the existing anchors showed a large majority of anchors were experiencing a loss of prestressed load, i.e., the residual load is smaller than the design load. This is not an unusual finding for anchors in Taiwan. The loss of prestressed anchor load can be a result of high groundwater level and weak/fractured geological conditions of the anchored slopes. When the prestressed load is decreased, it should take a close look on the sign of slope instability such as the unusual surface and groundwater flow and any cracks development on the retaining structure and/or on the slope surface. If no sign of slope instability is observed, slope is likely still under stable condition and the tie-back ground anchors are in good balance with the current slope condition, even though the prestressed anchor load may have decreased. Under this situation, there is no immediate need to re-stress the anchors back to the original design load.

5. REMEDIAL MEASURES FOR CORRODED ANCHORS

Although many inspected anchored slopes show no sign of instability in Taiwan, a large number of anchors are suffering steel strand corrosion problem. There is an urgent need to prevent the rusting condition of existing ground anchors from getting worse. To do so, cement grout, which was low cost and commonly used, was injected to fill up the voids below the anchor head of the existing anchors to stop further corrosion on steel strands. This work could be carried out by drilling two holes from outside of the anchor to reach the void under the anchor head first (Figure 11). One hole was for cement grout injection; the other was for air ventilation. Cement grout (water/cement ratio = 0.5) was injected to the void with grouting pump. Since cement grout may settle or leak out from the anchor hole, pumping process may have to repeat several times and it could be time consuming. To make sure cement grout had filled up the anchor hole, an intravenous (IV) injection method is adopted as the final step of this remedial treatment. When the cement grout was effluent from the ventilation hole and was in balance with the grout supply bottle, then it could be certain that the void underneath the anchor head was filled with cement grout and the steel strands were safely covered with cement grout.

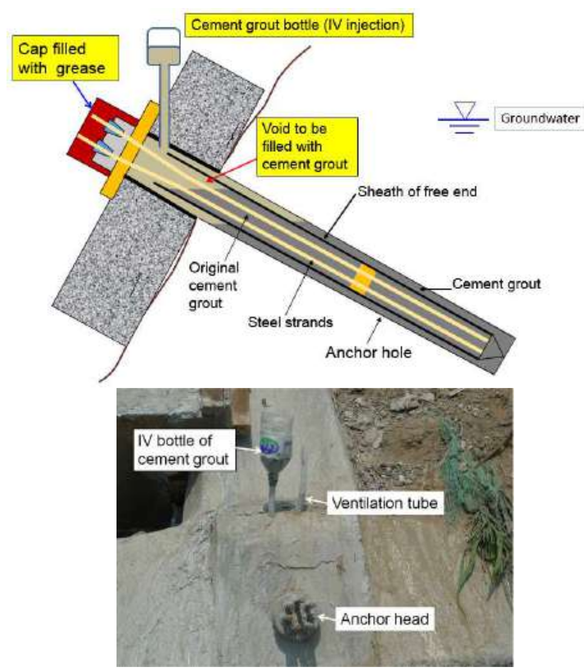

Figure 11 Fill up the voids under anchor head with cement grout for the existing anchors

6. CORROSION PROTECTION FOR NEW GROUND ANCHORS

To enhance the corrosion protection of ground anchor, the attention to details must be exercised, especially the free anchor end under the anchor head and the components of anchor head (Figure 12). Although the strands made of non-corrodible material such as FRP or carbon fibre had been considered as the replacement material for the traditional steel strand, the high cost of these materials and lack of local experience had complicated their application on ground anchors in Taiwan. In comparison, steel by far is the most acceptable material in the civil engineering industry. Its longevity can be ensured by coating the steel strands with epoxy or cement grout and plastic sheath. Since cement grout is the most commonly used and the least expensive grouting material, a cement grout based corrosion protection method for ground anchor is recommended by the Taiwan Geotechnical Society and will be reported here.

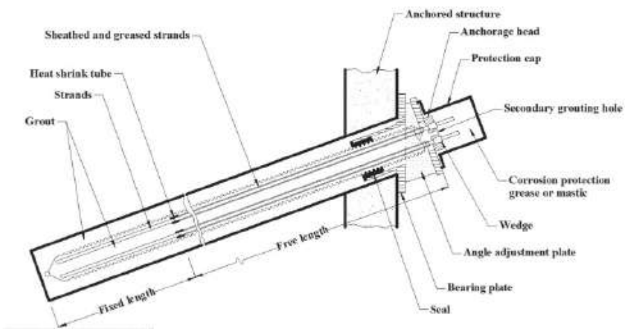

Figure 12 Typical anchor assembly with double corrosion protection and with no seal device between free and fixed anchor ends

To improve the corrosion protection under anchor head, a specially designed bearing plate assembly at the anchor head was shown here (Figures 12 and 13). Its effectiveness on upgrading the corrosion protection of ground anchors had been evaluated by means of electrical resistance measurement method (Liao et al., 2017b). This bearing plate assembly consists of (1) an extension pipe with rubber seal to protect the bare steel strands under anchor head; (2) grouting opening and ventilation hole for filling up the annular space outside the plastic sheath; and (3) the angle adjustment plate to keep the anchor head in-line with the anchor hole. Cement grout is injected through the bearing plate and the ventilation hole is to prevent the air from being trapped inside the anchor during cement grouting. The rubber seal on the extension pipe is to stop the groundwater flowing to the plastic sheath. The space inside the extension pipe will also be filled with cement grout or anti-corrosion grease.

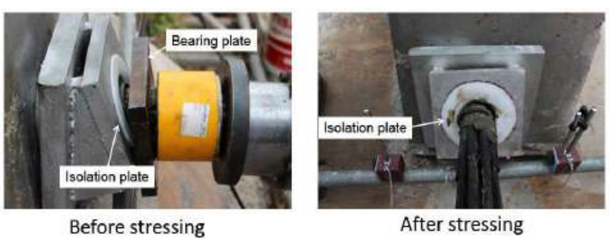

Figure 13 HDPE isolation plate used in ERM before and after stressing

For permanent anchors used in anchored slopes, double corrosion protection is required. Figure 12 illustrates a typical anchor assembly for a double corrosion protection anchor. The entire anchor length is sheathed with a corrugated sheath (Hana, 1982). There is no seal device, which commonly used to separate the fixed end grouting from the free end grouting, to facilitate the grouting process. It can minimize the risk of not filling up the whole anchor with cement grout. On the free length of anchor, each strand is smeared with corrosion protection grease and then sheathed with a polyethylene (PE) tube. The PE tube extends from the bottom of the free length and ends right under the anchor head. Thus, the entire free anchor length (the sheathed strand length) is free to deform during stressing (this assumption will be examined by the field test described later). At the bottom of the PE tube, a heat shrink tube is used to seal off the end to prevent cement grout from leaking in. Having been sheathed, the steel strands along the free length are separated from the cement grout and are free to deform during anchor stressing and afterward. In other words, the steel strands along the free length can be deformed in response to changes in anchor load during the entire service time of the anchor. The effectiveness of water tightness of anchor was tested by electrical resistance measurement method to make sure no groundwater was able to seep in and get in contact with the steel components of anchors.

After all the corrosion protection measures had been done for the ground anchors, the electrical resistance measurement (ERM) method adopted by the Swiss Highways and Swiss Railways Departments (Fischli, 1997) was used here to check the integrity of the corrosion protection of the stressed ground anchor. To electrically separate the ground anchor from the surrounding ground, an HDPE isolation plate (in white color) was placed between anchor head/load cell and bearing plate during ERM test (Figure 14). Table 5 shows the results of the ERM test carried out on anchors of an anchored slope along the national expressway in Taiwan. All the measured Ohm values of test anchors are well above the minimum value of 0.1 M Ohm suggested by the Swiss. It indicates that the encapsulation of the anchor components by plastic sheath and/or cement grout and the HDPE isolation plate of the test anchors all functioned properly. The integrity of corrosion protection of the test anchors was confirmed.

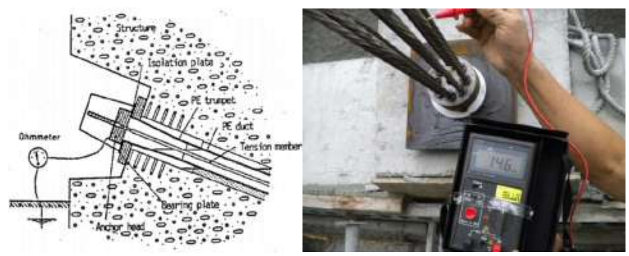

Figure 14 ERM on stressed ground anchor (500V DC) (Fischli, 1997)

Table 5 Measured electrical resistance results on stressed ground anchors

Anchor	Measured electrical resistance (Ohm)
No. 1	99.8M Ohm > 0.1M Ohm
No. 2	146.0M Ohm > 0.1M Ohm
No. 3	189.3M Ohm > 0.1M Ohm

7. A SIMPLE MONITORING METHOD FOR ANCHOR LOAD CHANGE

Anchor load monitoring is an important measure to check the stability of an anchored slope. A clear load increase of stressed anchors on anchored slope can be an indication of downward sliding of a slope. But long-term measuring of anchor load change is not a straightforward task. Typically, anchor load change is measured with the electrical load cells or by lift off test. However, the electrical load cells installed on the anchors can only survive for a limited period of time when used in an outdoor environment (Dunnicliff, 1988). On the other hand, the lift off test is simple in principle but often it has site accessibility problem when carried out on the existing anchored slope. Alternatively, a simple method for reliably measuring the anchor load change over an extended period is proposed and implemented in Taiwan (Liao et al, 2017a).

The proposed anchor load change monitoring device is similar to the tell-tale device (Dunnicliff, 1988) in principle. The tell-tale, which uses an unstressed rod mounted alongside a stressed structure member, can be used to indicate the change in length of the stressed member. The change in length is then converted to strain or change in load provided that the length of the stressed structure member is known. Nevertheless, the tell-tale is actually a foreign object mounted to a strand of ground anchors; thus, extra care is required to facilitate the survival of the tell-tale during anchor construction. Practically, successfully installing a tell-tale is difficult during routine anchor construction. The method proposed here is to transfer the anchor itself to a tell-tale device..

The proposed method for measuring the anchor load change basically alters nothing in the anchor assembly except for adding one extra strand as the reference strand. As depicted in Figure 15, the reference strand is not connected to the anchorage head by omitting the lock-in wedges. Accordingly, the anchorage head moves when the anchor load changes because of slope movement, deterioration of anchor components or any other causes. In comparison, the reference strand is not engaged to the anchorage head. So a relative deformation of the reference strand to the engaged strands is generated because of the anchor load change. If the anchor load decreases, the reference strand extends outward with respect to other engaged strands (negative δ). On the other end, if the anchor load increases, the reference strand is shortened (positive δ).

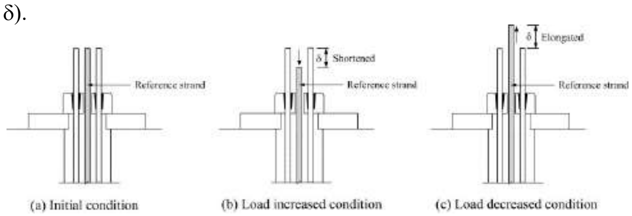

Figure 15 Principle of the proposed anchor load change measurement

If the measured relative deformation (δ) of the reference strand is known, the change of the anchor load (ΔP) can be estimated from the following equation:

$$\Delta P = \frac{\delta \times E \times \Sigma A}{L_{eff}} \tag{1}$$

where δ is the relative deformation of the reference strand in response to anchor load change; E is Young's modulus of steel strand, and equals 2000 t/cm^2; ΣA is the cross-sectional area of all engaged steel strands (A = 0.9871 cm^2 for a 7-wire strand with a nominal diameter of 12.7mm; A = 1.3870 cm^2 for a 7-wire strand with a nominal diameter of 15.2mm); and L_{eff} is the effective free strand length.

Three test anchors were used to examine the effective free length of working anchors. The assembly of all test anchors was exactly the same, as that illustrated in Figure 12. Each anchor used seven 12.7mm steel strands (Grade 270) with a design free length of 15m and design fixed length of 10m. Among the strands, six were engaged to the anchorage head and one was used as the reference strand. In this field test, several pre-determined loading cycles were applied to the anchors during the anchor suitability test (ISO/DIS 22477-5, 2010). The initial length of the reference strand extruding from the head of the jack were measured using a caliper. Repeat this procedure for each loading cycle and then subtracting the initial reading to obtain the relative deformations of anchor head at different loadings. Since the deformation of the reference strand was measured from the head of the jack, the free length of this test should be the summation of the sheathed strand length and the strand length inside the jack and load cell. Through a substitution of the measured relative deformations (δ) and the anchor load changes at each corresponding loading cycle into Eq. 1, L_{eff} of the test anchors was calculated and compared with the design free anchor length in Figure 16. In general, there is only 1%–2% (0.16m/16m or 0.34m/16m) difference in length, demonstrating that the calculated effective free length (L_{eff}) was very close to the design (i.e., sheathed) free length under a working anchor load. Thus, if the anchors were assembled as shown in Figure 12, the design free length could be used directly in Eq. 1 for the calculation of anchor load change.

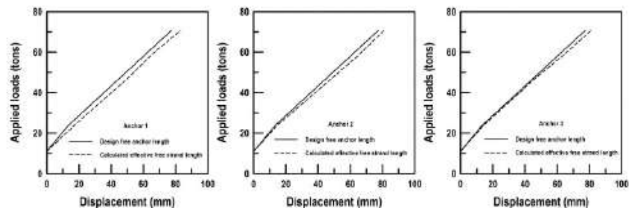

Figure 16 Comparison of applied load-displacement relationship between the design free anchor length and calculated effective free strand length

The residual load (P_r) of the anchor at the time that δ is measured is equal to the summation of the anchor load change ΔP and the initial locked-in load (P_i) of the anchor:

$$P_r = P_i + \Delta P \tag{2}$$

Three field anchors were used to check the locked-in loads with lift-off tests to verify the accuracy of the proposed method. Each anchor used 7 strands (12.7mm-ϕ) with the design free length of 15m and design fixed length of 15m. Among them, 6 were engaged strands and one was the reference strand. Prior to the test, a set of split ring (approximately 1 cm in thickness) was placed under the anchor head of test anchors. Lift-off test was performed to determine the efore and after the removal of the split ring. As shown in Figure 17, the reference strand clearly extruded out from the engaged strands after the split ring was removed and the load was reduced. The threads that appeared on the anchor head in the photo were for the stressing of the lift-off test. But the proposed load change measurement method here can be used easily with any regular anchor heads. The load change determined from the lift-off test was compared with that calculated from Eq. 1 by using the relative deformations of the reference strand measured before and after the removal of the split ring (Figure 18).

Figure 17 Relative deformation of reference and engaged strands caused by anchor load decrease

Table 6 lists the data of test anchor, results from the lift-off test, and calculated loads. In general, the load change calculated from Eq. 1 was in good agreement with that determined from the lift-off test. The average difference ranges from 1.4% to 4.7 % relative to the initial locked-in load (P_1). This indicates that this simple method can be satisfactorily used to monitor the long term anchor load change with reasonable accuracy.

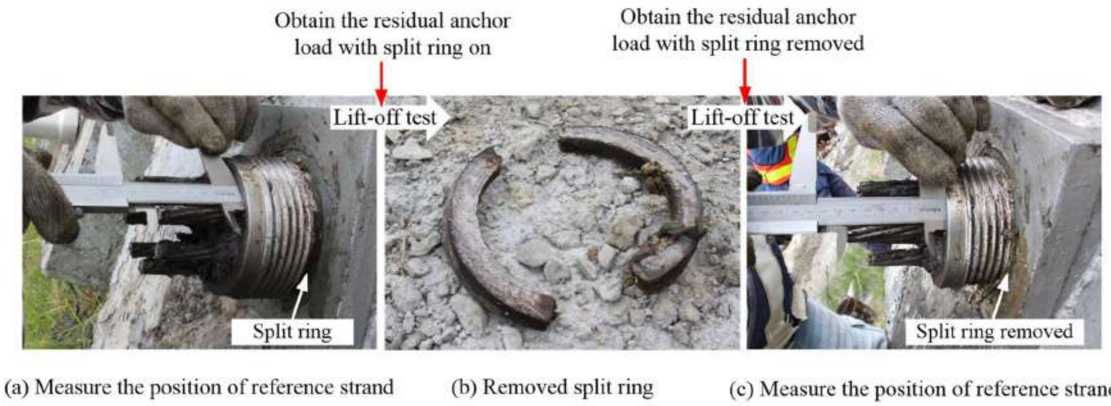

Figure 18 Relative deformations of the reference strand measured before and after removal of the split ring

Table 6 Test anchor data and measured and calculated lift-off loads

Anchor	From Lift-off Test (tons)				δ (cm)	$\Delta P_{calculated}$[d] (tons)	$\Delta P_{calculated}/P_1$ (%)	ΔP_{diff}[e]$/P_1$ (%)
	P_1[a]	P_2[b]	$\Delta P_{measured}$[c]	$\Delta P_{measured}/P_1$ (%)				
1	53.5	42.5	10.5	19.6	0.96	7.96	14.9	4.7
2	46.0	37.0	9.0	19.5	0.95	7.88	17.1	2.4
3	54.0	45.5	8.5	15.7	0.93	7.71	14.3	1.4

[a] P_1: residual load before washer removed
[b] P_2: residual load after washer removed
[c] $\Delta P_{measured}$: measured anchor load change
[d] $\Delta P_{calculated}$: calculated anchor load change from Eq. 1
6 strands (12.7mm-ϕ) per anchor engaged with anchorage head
Design free strand length = 15m, Design fixed length = 15m
[e] ΔP_{diff}: difference of anchor load change = abs ($\Delta P_{measured}$-$\Delta P_{calculated}$)

8. CONCLUSIONS

The sudden failure of a tied back cut slope of national expressway No. 3 in Taiwan revealed the problems of ground anchors of anchored slopes. In the meantime, it also changed the practice of construction and maintenance of the anchored slopes in Taiwan. Based on the findings from the nationwide investigation on the roadside slopes along expressways, highways, and railroads, it had been found that a large majority of ground anchors had voids under anchor head and the steel components of anchor were subjected to different extents of corrosion problem. The following conclusions are drawn from the exercise of overhauling program for anchored slops in Taiwan:

(1) Field anchors which suffered various extents of corrosion are in a delicate balance between residual tie-back load and residual material strength of various anchor components. Any increase in loading or any further decrease in material strength due to corrosion may trigger a chain-reaction failure among anchors. The breakage of anchor strands will result in a sudden and fast moving dip slope landslide like the one occurred in national expressway No. 3.

(2) Not properly sealed void underneath the anchor head is the main area of steel strands corrosion. When found during the existing anchors inspection, it was treated immediate by sealing off the voids with cement grout to stop further corrosion. For the new anchors, the corrosion protection of the anchors was upgraded by slightly modifying the assembly of steel strands as well as the assembly of anchor head. To minimize the risk of not filling up the whole anchor with cement grout, the seal device which commonly used to separate the fixed end grouting from the free end grouting of anchor is removed from the strand assembly of new ground anchors.

(3) Normally, a reduction factor is applied to the corroded anchors and extra anchors are installed to make up the loss of anchorage capacity due to corrosion. If no sign of slope instability is observed, the remedial measures were to resume the original slope stability again by installing additional anchors to the slope, even though the original anchor load might be over-designed.

(4) The new anchors installed should have good corrosion protection and hopefully can show the sign of anchor load change by itself. The anchor illustrated in Figure 12 has demonstrated its effectiveness on corrosion protection and its ability to easily detect the long term change of anchor load

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