Ground anchors corrosion – the beginning of the end

Hung-Jiun, Liao^{1,*}

¹ Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

Abstract. Ground anchor corrosion is a common problem for anchored slopes in Taiwan. It is partly due to the humid climate condition and abundant groundwater in the slope and partly due to poor corrosion protection of anchor design and construction. In 2010, an anchored slope at Taiwan National Freeway No. 3 failed suddenly after 13 years of service. It buried 3 cars and killed 4 people. It caught the public's attention and initiated the island-wide program on over hauling the anchors slopes in Taiwan. Since this event, the Ministry of Transportation and Communication (MOTC) of Taiwan government had launched an extensive inspection and maintenance program for the existing anchored slopes along the freeways, highways, and railways. Totally, more than 100,000 ground anchors had been inspected. This paper will evaluate the findings from this inspection program. It includes (1) the status quo of the anchors regarding the corrosion condition and the residual load that remained on the existing anchors; (2) remedial measures taken to sustain the serviceability of existing corroding anchors; (3) measures taken to enhance the long-term durability of new anchors without changing the strand material and the practice of anchor construction commonly used by the local contractors.

1 Introduction

Ground anchors are commonly used in Taiwan and elsewhere in the world to tie back cut slopes or to enhance the stability of natural slopes. So far, most of the anchors have served their purpose well to stabilize slopes. However, the long-term performance of ground anchors has been constantly questioned by some engineers in terms of the durability of anchor components and the loss of anchored load during the the life cycle of the anchor. In fact, the use of ground anchors to tie back slopes is not without failures (big or small) in Taiwan [5]. Some local governments even tried to restrict the use of ground anchors for slope stabilization due to its uncertainty of the long-term performance. But the restriction attempt was finally abounded because the ground anchor was such a handy tool for geotechnical engineers and many more ground anchors were actually installed to stabilize the cut slopes since the restriction was issued.

In 2010, an anchored slope failed suddenly and catastrophically after 13 years of service at Taiwan National Freeway No. 3 (Fig. 1) [4,6]. This failure case had fundamentally changed the ways of design and maintenance of anchored slopes in Taiwan. After this event, the

* Corresponding author: hjliao@mail.ntust.edu.tw

Ministry of Transportation and Communication (MOTC) of Taiwan government had launched an extensive island-wide inspection and maintenance program on the existing anchored slopes along the freeways, highways, and railways [7][10]. This paper will evaluate the findings from this program. The problems of anchors under humid climate and high groundwater conditions of Taiwan will be addressed. Finally, the remedial measures taken to sustain the serviceability of existing anchors and to secure the long-term durability of the new anchored slopes are proposed.

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

2 Inspection of existing anchors

The following steps had been taken to inspect the existing anchored slopes and evaluate the residual stability of anchored slopes along freeways, highways, and railways:

- (1) Visual inspection and hammer tapping on the concrete protection cap of anchors (Fig. 2): The integrity of concrete cap can be easily detected by hammer tapping. Special attention was paid to find the cracks on the concrete cap and the sign of groundwater leaking out from under the concrete cap. If there is/was constant water seeping out, calcium carbonate (white stain) will deposit under the concrete cap and can be easily spotted.

Fig. 2. Visual inspection and hammer tapping on the concrete cap of anchor.

- (2) Remove the concrete cap and inspect the steel strands and the wedges on the anchor head (Fig. 3). 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.

Fig. 3. Remove the concrete protection cap of the anchor head.

- (3) Use endoscope to inspect the condition of steel strands beneath the anchor head (Fig. 4): If there was void under the anchor head, the strands were inspected using an endoscope which provided a close-up look on the corrosion condition of steel strands. Generally, the corrosion condition of steel strands beneath the anchor head may not necessarily correspond to the external appearance of anchor head components observed in Step 1.

Fig. 4. Use endoscope to inspect the corrosion condition of steel strands under anchor head.

- (4) Carry out lift off test to determine the residual anchor load: A lift off test apparatus as shown in Fig. 5 is needed in this step. Extra caution must be exercised to avoid breaking the rusty steel strands during lift off test if anchors were suffering serious strands corrosion. It is quite normal to have some change (say $\pm 20\%$) on anchor load over the life cycle of anchors. But if the residual load goes beyond 120% of the design anchor load, it can be an indication of slope movement. Further inspection and evaluation are needed to ensure the stability of the slope. If the anchor load falls below 80% of the design load, it may result from the creep of the fixed end, the shortening of the free end, slip between wedges and strands and corrosion of anchor head components. If no sign of slope instability was observed, the anchor load was likely to be in balance with slope mass. No immediate action needs to be taken.

Fig. 5 Lift off test to determine the residual anchor load.

Table 1 shows the scores of an example anchor obtained from the above-mentioned inspection process. This example anchor got a score of 70.75 and was graded as “Fair” (Table 2). Its residual load was between 0.8 to 1.1T_w. However, it got a low score on strands corrosion (seriously corroded). This is the type of anchor which needs further attention. The residual anchor load was higher than the design. It indicated that the slope might have some downward movement. Since the strands were seriously corroded, a sudden failure might occur on this slope due to strand breakage.

After gathering the inspection results from the slope anchors, the overall score of this particular anchored slope can be obtained by adding up the total scores (□) of each inspected anchor and then dividing by the number of inspected anchors. The average overall score (□) can be obtained and used to category grade this anchored slope (Table 3).

Table 1. Example case of an anchor inspection results.

No.	Item	weighting	Score
1	Visual inspection of anchor head protection cap	10%	10
2	Inspection on steel strands and wedges of the exposed 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 2. Category grades of a single anchor based on the inspection scores.

Total score	Category grade	Remarks
0	X (out of function)	
$\beta \leq 30$	A (Very poor)	
$30 < \beta \leq 55$	B (Poor)	
$55 < \beta \leq 80$	C (Fair)	■
$80 < \beta$	D (Normal)	

Table 3. Category grades of an anchored slope based on score summation of inspected anchors.

Overall score	Category grade	Remarks
$\alpha \leq 30$	A (Very poor)	
$30 < \alpha \leq 55$	B (Poor)	
$55 < \alpha \leq 80$	C (Fair)	
$80 < \alpha$	D (Normal)	

Note: $\alpha = \Sigma$ total score of inspected anchors / No. of inspected anchors

3 Remarks on lift off test

Among the four steps inspected, the scores obtained from steps No. 1 to 3 are qualitative. Only step No. 4 can yield the quantitative lift off load. But the lift off test is costly and not easy to work on if the anchors are high in the anchored slope. It might be useful to correlate the images taken from the endoscope inspection with the residual anchor loads determined from the lift off test.

Five anchors from the anchors remained on the failed slope of Freeway No. 3 were chosen for lift off tests (Fig. 6). The results of the lift off tests, such as lift off load and maximum applied load, are listed in Table 4. Among the five lifted off anchors, two yielded residual loads of more than 90 ton (=1.5T_w, T_w = design anchor load = 60 ton); two yielded lift-off

loads of 43.65 ton and 54.8 ton (less than T_w). For the latter, steel strands broke when the load was further increased to 50 ton and 60 ton respectively. The last one yielded a lift-off load at 65.9 ton (larger than T_w) but strands broke shortly after the load increased to 68.7 ton. The ultimate load of corroded anchors roughly varied from 45% to 80% of the yield load of steel strands depending on the seriousness of corrosion.

Fig. 7 shows the endoscopic image taken before the lift off test. In general, all anchors were subjected to serious strands corrosion and should be classified as unacceptable following the BSI requirements for ground anchorages [1]. In fact, some wires of the strand were broken even before running the lift off test (Anchor III). Some strands were in moist condition and weeds grew inside the anchor hole (Anchor V). But there is no clear correlation between the remained anchor capacity (lift-off load) and the extent of surface corrosion of steel strands. For example, the surface corrosion of steel strands is no better than Anchors III, IV, and V. But the maximum pull-out load of Anchors I &II was about 50% higher than the other three anchors. No strand breakage occurred in Anchors I & II while Anchors III, IV, and V showed strand breakage at their maximum loads. It was also observed that the wires in the strands suffering the most serious corrosion or subjected to the most stressing load broke first during stressing. In other words, a wire-by-wire breaking pattern within a strand was observed; followed by a strand-by-strand breaking pattern within an anchor. After the breaking of an individual anchor, its load was passed to other anchors and subsequently caused a chain-reaction type of anchor failure. As a result, a sudden slope failure occurred

Table 4. Lift off test results of five anchors remained on face slope of Freeway No.3 landslide.

Test No.	Series No.	Design load T_w (ton)	Lift off load (ton)	Max applied load (ton)
Anchor I	B-3-26	60	No lift up	93.8
Anchor II	B-4-28	60	88.2	90.0
Anchor III	B-2-22	60	54.8	60.0*
Anchor IV	B-5-15	60	65.9	68.7*
Anchor V	B-4-10	60	43.6	50.0*

*strands broken

Fig. 6. Location of anchors chosen for lift-off test and their test results.

As shown in Fig. 8, five out of seven strands of Anchor III were broken at a location within 1 m from the anchor head during the lift off test. Two strands remained in the anchor hole without breakage. When examining the broken strands, the surface of the strand was in wet condition (Fig. 8).

Fig. 9 shows the close-up look of each broken strands of Anchor III. Obviously, every strand suffered different extents of corrosion. Those (No. 3 & 5) with less corrosion could

take more load during lift off test and showed some trace of intact steel at the broken face; those with more corrosion showed no trace of intact steel and were expected to take much less loading. In other words, once the strands in the anchor hole begin to corrode, their breakage capacities decrease but not at the same paces. Hence, when the strand is stressed to its breaking point, the wires in the strand broke in a one-by-one pattern rather than in a grouped pattern. So, the overall pullout capacity of a rusty anchor is not the summation of all the strands in an anchor. For example, for the three anchors broken during lift-off test, anchors broke at a loading only marginally larger than the lift-off load, but significantly smaller than the design anchor load.

Fig. 7. Images of endoscope inspection taken before the anchor lift-off test.

Fig. 8. Wet broken strands of Anchor B-2-22 (Anchor III).

4 Alignment of anchor head and steel strands

Anchor consists of several components such as steel strands, anchor head, and anchor hole. In many cases, the face of ground retaining structure is not perpendicular to the alignment of anchor hole. So an angle adjustment plate is needed to keep the anchor head in the perpendicular position to the anchor hole. The example shown in Fig. 10 is to illustrate the failure to use an angle adjustment plate to maintain a perpendicular position of anchor head to the steel strands coming out from the anchor hole. Having such a situation, it will damage

the steel strands and also reduce the stressing load transferring to the fixed end of the anchor. In addition, the wedges will not be able to grip the steel strands firmly on to the anchor head due to unevenly distributed loads among the wires in the steel strands. Therefore, the alignment control for all the components of the ground anchor is crucial for the anchor construction. It requires precision, practice and patience from the ground anchor contractor. In fact, the angle adjustment plate can do more than just adjust the angle. It can also be used as an indicator for the soundness of free end cement grouting of the anchor. Fig. 11 shows a specially integrated angle adjustment plate and bearing plate assembly. This bearing plate assembly consists of (1) an extension pipe with a rubber seal to prevent groundwater from seeping into the inside of the plastic sheath and moistening the unsheathed bare steel strands right under the anchor head; (2) grouting opening and ventilation hole to completely fill up the annular space between the plastic sheath of the free anchor length and drill hole; and (3) the angle adjustment plate to keep the anchor head in alignment with the anchor hole. Cement grout is poured into the opening of the assembly (Fig. 11), a ventilation hole is predrilled on the bearing plate to facilitate the cement grouting process under the anchor head. The space inside the extension pipe will also be filled with cement grout or anti-corrosion grease later.

Fig. 9. Close-up look of five broken strands of Anchor B-2-22 (Anchor III).

Fig. 10. Schematic diagram for the alignment problem of anchor head with steel strands.

In addition to the bearing plate assembly, a completed cement grouted ground anchor also includes the anchor head assembly and other parts of anchors as schematically shown in Fig. 12. It should be noted that the grout seal device which is typically used in the traditional anchors to separate the free end grouting and fixed end grouting had been removed from the anchor assembly to facilitate the grouting process. Originally, this grout seal device is to prevent the cement grout from flowing into the free anchor end during the fixed end grouting and allow the strands in the free end elongate during anchor stressing. But this function can be taken over by the strand assembly shown in Fig. 12. Each individual steel strand was sheathed with PE tube on the free anchor length and the PE tube was sealed at the bottom with heat shrink tube. Without the grout seal device, it can make the cement grouting work of the anchor much easier and with a better grouting quality. The effectiveness of water tightness of anchor can be tested by electrical resistance measurement method if required.

Fig. 11. Schematic diagram of modified bearing plate assembly [9].

Fig. 12. Schematic diagram of the proposed ground anchor.

Lastly, the alignment of the stressing jack with the anchor hole is also an important factor needed to address. The hydraulic jack itself is quite heavy. It needs great patience and efforts to keep it in line with the anchor hole when the anchors are high up on the slope and with an inclined angle. Under this difficult construction condition, it is not easy to keep a good alignment between the jack and anchor hole. Failure to keep the alignment may result in problems such as unevenly stressed strands and wedges. Fortunately, this problem can be solved easily by installing locating pins on the bearing plate to keep the jack in the right position (Fig. 13). With the locating pins, the jack can be mounted to the bearing plate at the right position. So the load reading from the jack can be much closer to that from the load cell as demonstrated in Fig. 13.

Fig. 13. Comparison of load readings from jack and load cell with and without locating pins

It is understood that the anti-corrosion capacity of the ground anchor can be significantly improved by using reinforced fibre glass or carbon fibre strands or using the epoxy coated steel strands to replace the traditional steel strands. However, the government system is generally slow to pick up new materials or new methods for the civil engineering work, especially the cost of the new materials or new methods tends to be higher. If not using new material, then using the factory-made ground anchor assembly can be an alternative. Factory made anchors can provide a better control on the details of anti-corrosion measures compared to those assembled on the job site. However, due to the fact that factory made pre-fabricated

anchor cannot always meet the changing ground or construction conditions on site, the pre-fabricated anchors are not popular in the ground anchor industry. The proposed ground anchor system shown in Fig. 12 does not involve any new material or require any new construction methods. But it can provide the same anti-corrosion function needed for the permanent use of anchors. So, it is relatively easier to be accepted by the government agencies and also by the engineering design companies.

5 Monitor the anchor load change

Anchor load monitoring is an important practice for monitoring the stability of an anchored slope. But since ground anchors are mostly pre-stressed during the construction stage, so it is the change of stressed load which should be the concern of an anchored slope rather than the residual anchor load. For example, a clear load increase of anchor load on an anchored slope can be an indication of downward sliding of the slope. But long-term measuring of the anchor load change is not a straightforward task. Typically, anchor load change is measured with the electrical load cells or by lift off test. Although the electrical load cell is good at measuring the locked-in anchor load with high accuracy and can be linked to the automatic slope monitoring network, it can only survive for a limited period of time when used in an outdoor environment [2]. On the other hand, the lift off test is rather simple in principle but often has site accessibility problems when carried out on the existing anchored slope. Due to the above-mentioned restrictions, both load cell installation and lift off test cannot be carried out in large numbers. But limited numbers of anchor testing can further complicate the problem because it will be difficult to evaluate the status quo of the slope stability based on a limited amount of data, especially if these data are themselves scattering. To solve this problem, a **Smart Anchor** which can reliably measure the anchor load change over a long period has been developed and implemented in Taiwan [8].

The anchor load change monitoring device of Smart Anchor is similar to the tell-tale device [2] 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 in this paper is to convert the tell-tale device to become part of the anchor itself. Basically, this method alters nothing in the anchor assembly but introduces one extra strand as the reference strand. As depicted in Fig. 14, the reference strand is not connected to the anchorage head by omitting the lock-in wedges. In other words, the reference strand is not engaged in the movement of the anchorage head. So when the anchorage head moves (i.e., anchor load changes) because of slope movement, deterioration of anchor components or any other causes, the reference strand does not elongate or shorten as other engaged strands do. Then a relative deformation of the reference strand to the engaged strands is generated. If the anchor load decreases, the reference strand extends outward with respect to other engaged strands (negative Δ , Fig. 14c). On the other end, if the anchor load increases, the reference strand is subsided (positive Δ , Fig. 14b).

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:

$$\Delta P = \frac{\delta \times E \times \Sigma A}{L_{\text{eff}}} \quad (1)$$

where $\Delta\delta$ is the relative deformation of the reference strand in response to anchor load change; E is Young’s modulus of steel strand and equals to 2000 t/cm²; A is the total cross-sectional area of all engaged steel strands ($A = 0.9871\text{ cm}^2$ for a 7-wire strand with a nominal diameter of 12.7 mm; $A = 1.3870\text{ cm}^2$ for a 7-wire strand with a nominal diameter of 15.2 mm); and L_{eff} is the effective free strand length.

Fig. 14. Principle of the proposed anchor load change measurement

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 Fig. 12. Each anchor used seven 12.7 mm steel strands (Grade 270) with a design free length of 15 m and design fixed length of 10 m. 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 [3]. The initial length of the reference strand extruding from the head of the jack was measured using a caliper. Repeating this procedure for each loading cycle and then subtracting the initial reading is done to obtain the relative deformations of the 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 (=1 m). Through a substitution of the measured relative deformations ($\Delta\delta$) 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 Fig. 15. In general, there is only 1%–2% (0.16 m/16 m or 0.34 m/16 m) difference in length, demonstrating that the calculated effective free length (L_{eff}) was very close to the design (i.e., sheathed) free length in the anchor assembly under a working anchor load. Thus, if the anchors were assembled as shown in Fig. 12, the design free length could be used directly in Eq. 1 for the calculation of anchor load change.

The residual load (P_r) of the anchor at the time that $\Delta\delta$ 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 (12.7 mm- $\square$) with the design free length of 15 m and design fixed the length at 15 m. Among them, 6 were engaged strands and one was the reference strand. Prior to the test, a set of split rings (approximately 1 cm in thickness) was placed under the anchor head of the test anchors. Lift-off test was performed to determine the locked-in anchor loads before and after the removal of the split ring. As shown in Fig. 16, 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 load change measurement method proposed 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 (Fig. 17). Table 5 lists the test anchor data, 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_i). This indicates that this simple method can be satisfactorily used to monitor the long-term anchor load change with reasonable accuracy.

Fig. 15. Comparison of applied load-displacement relationship between the design free anchor length and calculated effective free strand length

Fig. 16. Relative deformation between the reference and engaged strands caused by anchor load decrease

Fig. 17. Relative deformations of the reference strand measured before and after the removal of the split ring

Table 5. Data of test anchors and results from lift-off test and from Eq. 1

Anchor	From lift-off test (tons)				δ (cm)	$\Delta P_{\text{calculated}}^d$ (tons)	$\frac{\Delta P_{\text{calculated}}}{P_1}$ (%)	$\frac{\Delta P_{\text{diff}}^e}{P_1}$ (%)
	P_1^a	P_2^b	$\Delta P_{\text{measured}}^c$	$\frac{\Delta P_{\text{measured}}}{P_1}$ (%)				
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 split ring removed

^b P_2 : residual load after split ring removed

^c $\Delta P_{\text{measured}}$: measured anchor load change

^d $\Delta P_{\text{calculated}}$: 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 [$\Delta P_{\text{measured}} - \Delta P_{\text{calculated}}$]

6 Conclusions

In 2010, the sudden failure of a tied back cut slope of National Freeway No. 3 in Taiwan had revealed the problems of ground anchors of anchored slopes in Taiwan and changed the practice of design, construction, and maintenance of the anchored slopes. Since voids under the anchor head were found in the majority of ground anchors and the steel components of anchor were corroded at different extents, anti-corrosion measures had been used to prevent the corrosion from happening on the existing anchors as well as the new anchors. The following conclusions are drawn from the anti-corrosion exercise on anchors in the anchored slopes in Taiwan:

- (1) Not properly sealed voids underneath the anchor head was found to be the main area of steel strands corrosion on the existing anchors. It was treated by sealing off the voids with cement grout to stop further corrosion. For the new anchors, a slightly modified strands assembly and anchor head assembly was used to upgrade corrosion protection without introducing the non-traditional ground anchor materials. The seal device which was commonly used to separate the fixed end grouting from the free end grouting of the anchor is removed from the new ground anchors to facilitate the grouting process and to minimize the risk of not filling up the whole anchor with cement grout.
- (2) A new anchor strands assembly method is proposed to measure the load change of pre-stressed anchors. It makes the load change monitoring become part of the anchor itself.

So it is simple, inexpensive, reliable, and above all very durable. It can be done easily during anchors construction. Although its accuracy may not be as good as the electrical load cells, it is good enough for practical purposes and can be used in large quantities. Having such an abundant load change information of tieback anchors, the engineers will be able to evaluate the stability of anchored slopes in a more confident way.

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