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Investigating the Performance of Ground Anchor Through The Failure Slope Disaster in Taiwan

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INVESTIGATING THE PERFORMANCE OF GROUND ANCHOR THROUGH THE FAILURE SLOPE DISASTER IN TAIWAN

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ABSTRACT

At milestone 3.1 km of the Formosa Freeway in northern Taiwan, a landslide occurred on April 25, 2000, causing nearly 200,000 m^3 of earth and rock to slump down onto the freeway below. Four people trapped in cars beneath the collapsed slope died. How such a tremendous slope failure could happen in dry weather without advanced warning is attributed to two key factors: (1) Long-term groundwater infiltration resulting in the softening of thin interlayer between sandstone and shale; (2) Ground anchor corrosion resulting in a decrease in slope stability. Together these two factors caused the slope to reach a critical limit resulting in a collapse. In Taiwan ground anchors have been widely used to improve slope stability along roadways for more than 40 years. After the Formosa Freeway slope collapse the government began a comprehensive survey to examine anchors on the slopes along all freeways. This paper uses finding from this survey as well as information from other slope failure investigations to examine the performance of ground anchors in Taiwan. The factors contributing to the failures of the permanent ground anchors and the required inspections/maintenances are discussed in addition to recommendations for improving design and construction.

INTRODUCTION

Ground anchors also known as tiebacks are designed to prevent landslides by resisting the slope forces that cause deformation. They are widely used in slope engineering projects because of their preventative approach as oppose to other mechanisms such as soil nails which are commonly used for remediation purposes after deformation has already begun. However, the degree of success of anchors depends on the quality of design and construction, and if not properly engineered slope failure can occur. Two examples of ineffective use of anchors and subsequent landslides, property loss and casualties in northern Taiwan are the 1997 Lincoln Mansion collapse in Hsichih; and the slope failure at the Formosa Freeway in 2010. With incidences such as these and increased rainfall in recent years, the design, construction and maintenance of ground anchors is a growing topic of concern in Taiwan.

DESCRIPTION OF SLOPE FAILURES AND CONTRIBUTING FACTORS

At milestone 3.1 km of the Formosa Freeway in northern Taiwan, a landslide occurred on April 25, 2000, causing nearly 200,000 m^3 of earth and rock to slump down onto the freeway below. Four people trapped in cars beneath the collapsed slope died, as shown in Fig. 1. That slope is 50 meters height cut dip-slope and reinforced by ground anchors.

Fig.1 Photos of slope failure on Formosa Freeway in Taiwan

Figure 2 shows the photo of original ground anchor slope condition. A 2D slope stability analysis was performed after the slope failure. The soil parameters are referring to the original design report and the investigation works of the disaster and modified by back analysis. Figure 3 shows one of output section of the slope stability analysis results. The softening effect of sliding rock (sandstone and shale rock layer) caused by ground water was taken into consideration by reducing the cohesive strength value (C) from 10 kPa to zero and friction angle value (ϕ) from 20° to 14°. Figures 4 to 6 are the slope stability analysis results for normal, earthquake and rainfall conditions, respectively. According to these stability analysis results, the 3m layer of sandstone/shale sitting above the rising groundwater level, significantly influences stability conditions and reduce the factor of safety from 1.55 to 0.9, which is below the stability specification requirement. In addition, the possible cases of tendon prestress lose in different percentage because of anchor corrosion or other defects with respect to the slope stability are analysis as shown in Table 1.

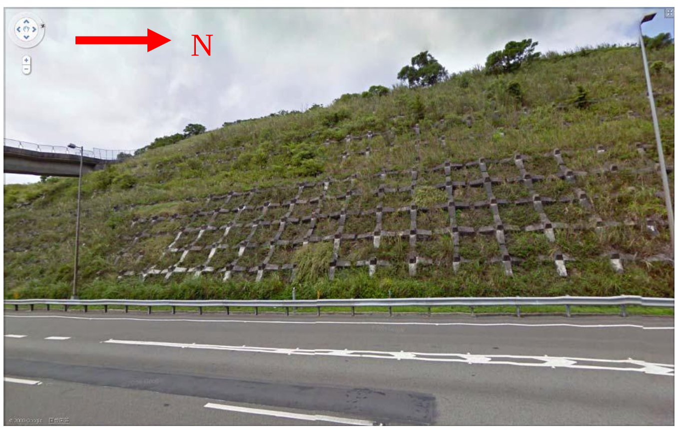

Fig.2 Photos of original ground anchor slope on Formosa Freeway before failure

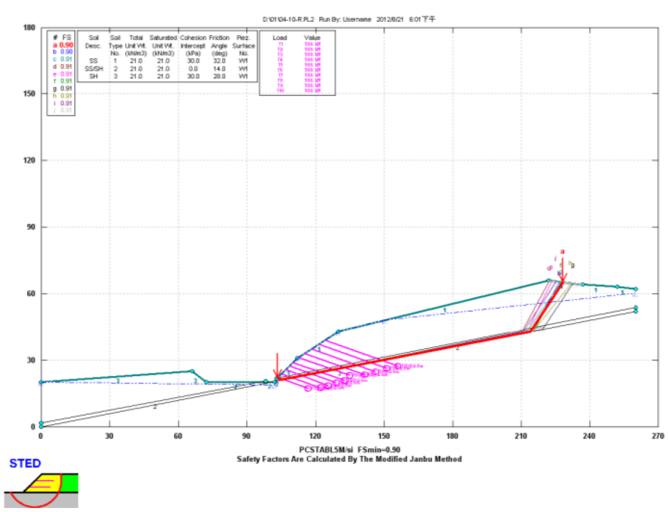

Fig. 3 Slope stability 2D analysis results

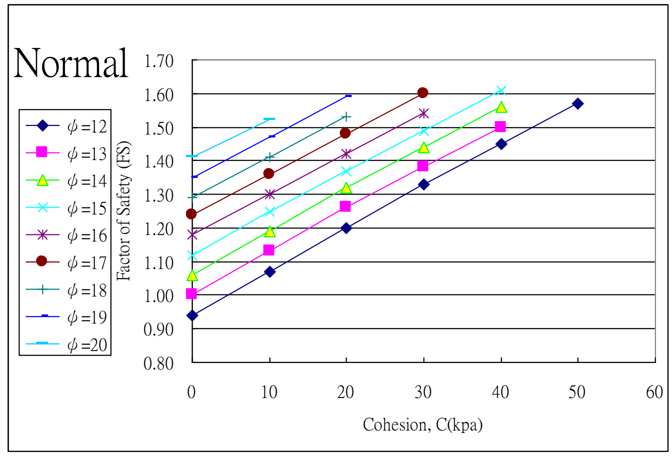

Fig. 4 Slope stability analysis results by reducing the strength value for Normal condition

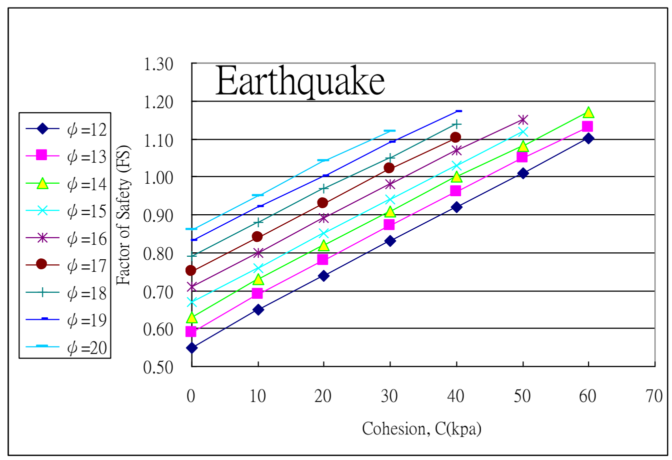

Fig. 5 Slope stability analysis results by reducing the strength value for Earthquake condition

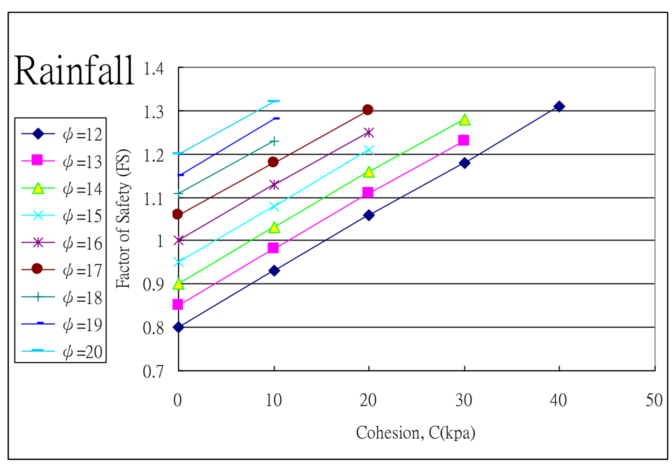

Fig. 6 Slope stability analysis results by reducing the strength value for Rainfall condition

Table 1 Slope stability analysis results for reduction anchor prestress caused by anchors corrosion or defects

Conditions and requirement		Factor of safety with respect to prestress reduction							
		100%	95%	90%	85%	80%	70%	60%	50%
N	≧1.5	1.52	1.5	1.48	1.46	1.44	1.4	1.37	1.33
E	≧1.1	0.95	0.94	0.93	0.92	0.91	0.89	0.87	0.85
R	≧1.2	1.32	1.3	1.29	1.27	1.25	1.22	1.19	1.15

Notes: N: Normal; E: Earthquake; R: Rainfall

The analysis results indicate the mechanism of slope failure to be attributed to two main factors. Surface water runoff seeping into existing cracks of the weathered sandstone weakened the sandstone/shale layers over time eventually contributed to the landslide. Also, corrosion of the ground anchor tendons compromised the strength of the system. Investigative results obtained after the slope failure showed that the tendons were degraded which would have inhibited their strength and durability under stress. However, the case of design earthquake condition may play another role on its slope stability, even though no such large earthquake was happen just before this slope failure, the past earthquakes could be gradually reduced the prestress of the ground anchors. Ultimately the runoff seepage compromised the rock strength in the interface of the sliding plane and then corroded tendons not able to withstand the sliding force allowed the slope to become unstable resulting in a landslide.

LIFE CYCLE MAINTENANCE MANAGEMENT FOR THE PERMANENT GROUND ANCHORS

Due to the creep of the ground anchor system, the load capacity of the tendon decreased during its lifetime. Creep is generally evaluated by the cyclic loading test. Figure 7 shows the schematic diagram of the ground anchor performance curve for its life cycle. It indicates that under normal conditions the performance of permanent ground anchors should remain higher than the required limit for the duration of its life. To meet this requirement the ground anchor needs to be inspected periodically and maintained as needed. If results indicated that the anchor has a decreased performance, measures should be taken to remedy this, as in curve A, Fig. 7. If the anchor is performing below the required limit, reinforcement is necessary, like curve B in Fig.7. Lastly, if performance is below the failure limit, the anchor should be replaced, shown in curve C, Fig. 7.

The expected performance of ground anchors for the design life includes tendons supporting the specified load amount, prevention of slope deformation, and resistance to corrosion. For the permanent ground anchor, periodic inspections and maintenance is needed during the design service life.

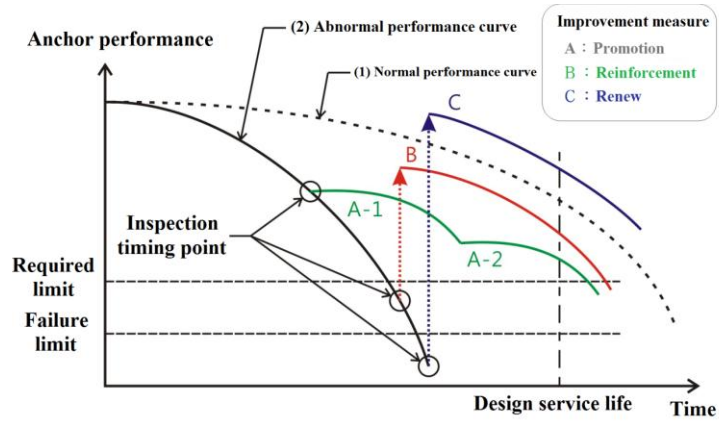

Fig. 7 Relationship between anchor performance and design service life (Modify from Public Worhs Research Institute，2008)

GENERAL PROBLEMS AND DEFECTS OF GROUND ANCHORS

After the landslide at Lincoln Mansion in 1997 claimed the lives of civilians, shown in Fig. 8, Taiwan took note of ground anchors. Requirements became more stringent for inspections, design and construction, and the use of ground anchors on permanent retaining structures were debated. Then, on April 25, 2000, tragedy struck again with the slope collapse on the Formosa Freeway. After a thorough inspection of the ground anchors on the freeway slope, several problems were discovered including insufficient inspections, inappropriate construction methods, and maintenance defects. The sources of the failures and inspection techniques are given as follows:

Fig. 8 Landslide of Lincoln Mansion in 1997

(1) Failure of anchor head: visual inspection for cracks or flaking of the concrete blocks, tendons shifted up, and departure or rotation of the anchor head, shown in Fig. 9. Efflorescence or groundwater seepage, rupture of the bearing structure and topsoil hollowed, along with other signs of disturbance.

(2) Integrity of components and corrosion: chisel out the concrete block to check the anchor head component and the

Fig. 9 (a) *Tendon fracture and shoot out*

Fig. 9 (b) *Depart or rotate of the anchor head*

Fig. 9 (c) *Cracks or flake off of the concrete blocks*

Fig. 9 Failure of anchor head and concrete blocks

tendons behind the head, an endoscope is used to observe the corrosion and breaking condition of the tendons behind the anchor head and the free length. Common problems include tendons with angular bending, shown in Fig. 10. Other conditions to look for include tendon shrinkage, corrosion of anchor heads and wedges, lack of grout in the free length, corrosion and breaking of tendons, shown in Fig. 11.

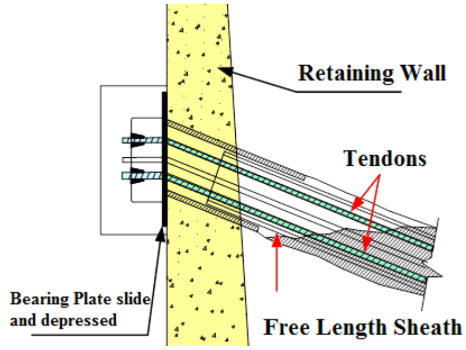

Fig. 10 (a) *Schematic diagram of tendons angular bending*

Fig. 10 (b) *Tendons uneven shrink caused by angular bending*
Fig. 10 Tendons angular bending conditions

Fig. 11 (a) Anchor head corrosion

Fig. 11 (b) Tendons shrink；Corrosion of anchor head and the wedges slip

Fig. 11 (c) Corrosion and breaking of free length tendons

Fig. 11 (d) Efflorescence or groundwater seeping out
Fig. 11 Anchor head corrosion and wedges slip and breaking of tendons

Fig. 12 (a) Anchor head sink in creep soil

(3) Residue loading (decrease or increase): The prestressing load after lock-off may decrease or increase because of creep, and/or wedge installation. An up-lift test is usually carried out to check the loading of the ground anchor. Under normal conditions, loading should be keeping between 0.8 to 1.2 times

Fig. 12 (b) Topsoil hollowed
Fig. 12 Prestressing lose conditions

Fig. 13 (a) Prestressing load increase because of slope sliding

Fig. 13 (b) Anchor head sink
Fig. 13 Failure conditions of anchor head

the design loads. However, the prestressing load may decrease because of soil creep, tendon corrosion and hollowed topsoil, shown in Fig. 12. On the contrary, the prestressing load may increase because of slope sliding, increased ground water pressure or swelling of the slope material, shown in Fig. 13.

Any of the condition mentioned above implies the slope may potentially fail, creating a dangerous situation.

DISCUSSION ON THE DESIGN PROBLEMS OF GROUND ANCHOR

The application of ground anchors in Taiwan has been more than 40 years. The current design concept follows the specification of "Standards for ground anchor design and construction" (Liao, 2001). Nevertheless, after the landslide occurred at the 3.1 km milestone of the Formosa Freeway in 2000, it was evident that the design of ground anchors still needs further improvements that include the following:

Soil and Rock Stratigraphy

The behavior of ground anchors and load capabilities is distinct for different subsoil strata. For instance, plants anchor into the soft rock or soil. In these conditions, the length of the bonded-end of the anchor usually cannot provide a stiff bonding strength; therefore, an enlarged anchor or single borehole with multiple anchors should be used. In the case of planting anchors into mudstone or fracture rock, the pre-stressing load may increase because of creep or a deeper sliding surface. For such cases an adjustable anchor should be chosen or the free tendon length in the anchor head should be about 20~30 cm for re-stressing in the future.

In the case of planting anchors into dip-slope conditions, the weakness of interlayer (e.g. shale) usually play an important role in the stability of the slope. The strength of interlayer may decrease to the point of residual values due to bedding slip or softening by groundwater. Therefore, caution should be exercised during site investigations and conservative parameters of shear strength are suggested. In addition, any mudstone or weathered, fractured, rock present on slopes should be closely examined as they can contribute to slope failure and are known to be common along freeways. Furthermore, the retaining structure can deform, tilt or crack and making the pre-stressing load lose. Therefore, a suitable structure type and surface treatment should be considered for the anchoring of a slope.

Corrosion protection

A special corrosion protection should be applied for the ground anchor in aggressive environments such as salt water, hot springs, waste yards, mining areas, etc. The investigation should carry out additional soil and ground water chemicals tests (e.g. PH value, resistivity, sulfate content).

The Post-Tensioning Institute （PTI）separated the classes of the ground anchor corrosion protection system into class I and class II. Selection of the corrosion protection class shall be based on the service life of the structure, aggressivity of the environment, consequences of tendon failure and incremental in-place costs. Furthermore, PTI (2004) shows clearly that for permanent ground anchors, aggressive conditions shall be assumed if the aggressivity of the ground has not been quantified by testing.

Recently in Taiwan, Several improvements on corrosion protection of ground anchors were developed, as shown in Fig. 14. They include: (1) using resin to replace cement grunt for the bond length; (2) for the unbounded length, coat the tendon with a small PE tendon sheath and fill with corrosion inhibiting grease inside the tendon sheath; (3) perform a second grouting in the unbounded length to ensure it is fully grouted; (4) use trumpet and water tight seal in the anchorage; (5) use anchorage cover and fill with corrosion inhibiting grease; (6) adoption of zinc-plated tendons or epoxy resin coating tendons for double protection. Some of these improvements will be describe in more detail later.

MONITORING INSPECTING AND MAINTENANCE CONSIDERATION

Until now, in Taiwan there was no specific standard or special provision to handle the maintenance and management of the permanent ground anchors. However, BS EN 1537(2000) has defined the design and execution activities and expressed that the designer should specify the maintenance for the ground anchor. The special executer should perform the maintenance as directed. Maintenance procedures should take into account the following:

(1)Access road for maintenance: setting an access road for persons and instruments to inspect and maintain for ground anchors.

(2)Creation of an inspection and maintenance plan: should provide inspection methods, items, quantities, frequency, critical value, evaluation and analysis for the inspection results and feasible improvement measures. A standard operation process (SOP) should be in place for the operational management department to execute.

CONSTRUCTION PROBLEMS DISCUSSION

Geologic conditions should be taken into account when constructing ground anchors. Common mistakes and suggestions are as follows:

Notes for ground anchor construction

(1) Ground anchor co-operate with the retaining structures
Permanent ground anchor construction need to co-operate with environmental conditions, suitable structure type should be selected based on the stiffness of slope soil. For instance, for an easy scouring soil slope choose a precast grid beam structure.

The ground anchor should be orthogonalized to the end plate on the retaining structure. If not orthogonal, an adjusted angle plate is needed to add the anchorage head to make them become orthogonal. In addition, the embedded casing in the retaining structure should sit in the correct angle and be fixed together with an end plate; this is usually conducted by welding them together to the rebar of the retaining structure before the structure concrete grouting. For non-orthogonal conditions, an unexpected angular bending will form in the tendon and reduce the performance of ground anchor.

To prevent ground water seepage into the anchorage head and the tendon behind it, the bearing plate is sealed by welding together with the trumpet in the anchorage. A rubber watertight seal is used to stuff the gap between the trumpet and the smooth PE sheath, as shown in Fig. 14.

When a cover is used, the space above and under the cover should be filled with a corrosion-inhibiting compound. Also, for restressable anchorages, the cover should be filled with a corrosion-inhibiting compound. If concrete is used to protect the anchorage head, setting either a plastic or steel cover and filled the cover with a corrosion-inhibiting compound and then a cast-in-place concrete is pouring to protect the anchorage head, as shown on Fig. 14.

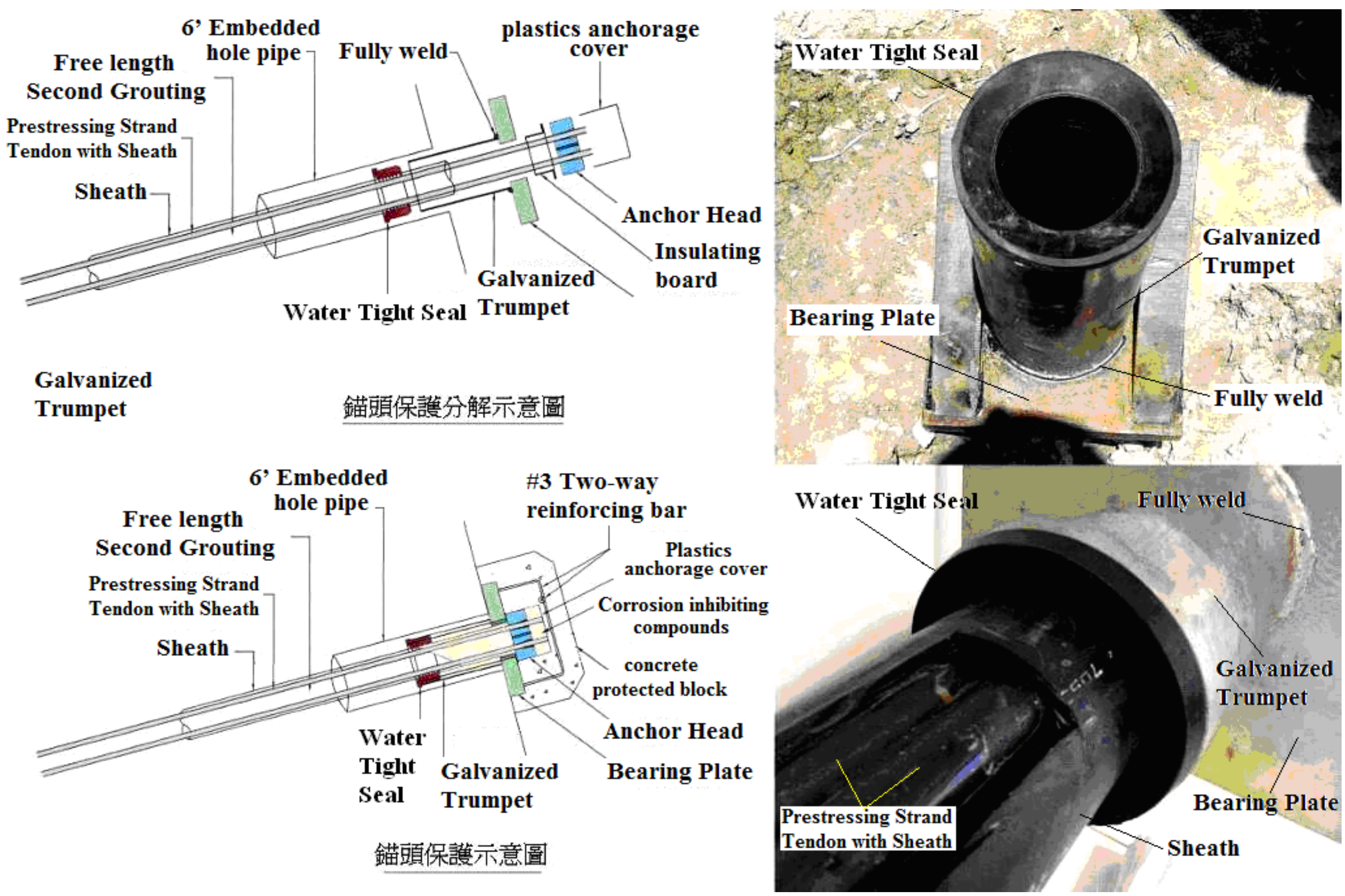

Fig. 14 Details of watertight seal connected with sheath and trumpet and anchor head (Good Earth Engineering Co., Ltd)

(2) Corrosion Protection Improvement for the Existing Ground Anchors

According to the inspection results obtained from the existing ground anchors of the slopes for freeways in Taiwan, more than half of the inspected anchors showed moderate corrosion in tendons due to unfilled grout in the unbound length. For the parts of tendons without grout protection, about 85% of the inspected anchors may become highly corroded in the future. Consequently, the problems of corrosion in anchorage and unbound length of the ground anchors in Taiwan need improved as soon as possible (Ho etc., 2011).

(a) Improvement for the corrosion protection in unbound length

The previous anchor systems commonly adopted in Taiwan are not watertight. Groundwater often seeps into ground anchor heads and into the free space of the unbound length. Moreover, due to the shrinkage and leakage of cement grout when the unbound length is grouted, it usually is not completely grouted behind the anchor head. Once the ground water seeps into this space, the tendons will eventually become seriously corroded.

To conquer this problem of uncompleted grout, there were two methods proposed for a case in northern Taiwan before comprehensive construction work commenced. These two methods consisted of performing tests of ground anchors in the field and grouting by gravity type and pressure type, respectively. The grouting effectiveness can be check by grubbing the ground anchor out and cutting the grouting block to observe the cross sections. Based on the observation results, the grouting sections were found to be full of grout. Even the most difficult dead space for grouting, just behind the anchorage head, was full. The reasons for this successful grouting can be attributed to three key points. (1) Setting air vent holes (grout exit when overflow) on top of the anchor hole; (2) Exclusion of air bubbles and draining of water while grouting; (3) Supplemental grout during shrinkage, this can be applied by gravity or pressure methods. Figure 15 shows the construction process for improved grouting for the corrosion protection in unbounded length.

(b) Improvement for the anchor head corrosion protection
Most of the ground anchor heads used in Taiwan, except for restressable anchorages, generally require concrete for protection that is applied by a second construction. Thus, a cold joint may exist between the anchor head and the retaining structure behind the bearing plate. This cold joint may allow leakage of water from rain, run-off and groundwater seepage causing corrosion of the anchor head, wedges and bearing plate.

Once the anchor head is corroded, it is very difficult to protect the wedges and tendons. To improve corrosion of the anchor head the rusts on the surface of the tendons and wedges must be cleaned out and coated with anti-rust paint. Finally, the cover is replaced after being filled with a corrosion-inhibiting compound, as shown in Fig. 16.

Fig. 15 (a) Drilling grout exit or air vent hole

Fig. 15 (b) Setting grouting pipe and air vent pipe

Fig. 15 (c) Exclude air bubbles and bleeding water in process of grouting

Fig. 15 (d) Grouting Completed

Fig. 15 Construction process of improvement grouting for the corrosion protection in unbound length

Fig. 16 (a) drilling screw hole on bearing plate

Fig. 16 (b) filled anchor head with corrosion-inhibiting compound

Fig. 16 (c) cover filled with 1/3~1/2 corrosion-inhibiting compound

Fig. 16 (d) fixed galvanized cover with bolts
Fig. 16 Construction process of corrosion-inhibiting cover

CONCLUSIONS AND SUGGESTIONS

This paper presents the performance of ground anchors by examining information collected from the landslide that occurred at the 3.1 km milestone of the Formosa Freeway in northern Taiwan, and other slope failure cases. The problems of permanent ground anchors and the maintenance work needed during the design life are discussed. The observations and conclusions are given in the following:

(1) The slope stability analysis results indicate the mechanism of slope failure occurred at milestone 3.1 km of the Formosa Freeway in northern Taiwan to be attributed to two main factors. They are runoff seepage compromised the rock strength in the interface of the sliding plane and then corroded tendons not able to withstand the sliding force allowed the slope to become unstable resulting in a landslide. However, the case of design earthquake condition may play another role on its slope stability, even though no such large earthquake was happen just before this slope failure, the past earthquakes could be gradually reduced the prestress of the ground anchors.

(2) Environmental aggression is a major impact for the anchors, consequently, the anchor corrosion protection is extremely important. In order to achieve the best results for the protection of ground anchors, different levels of ground anchor corrosion measures should be understood.

(3) For effective grout that prevents corrosion in the free length of ground anchor, at least three key points are relevant: setting up the vent near the highest point of the anchor hole; keeping the grouting process in a fully exhaust condition; let the slurry be mutually complementary at any time during the bleeding and shrinkage process of the grout. Ground anchor free length corrosion grouting should achieve full grouting conditions. Respecting whether or not such corrosion performance can fit the expected function in design life is still worth discussing.

(4) If the angle between the surface of earth retaining structures and ground anchors is not orthogonal, or the angle plate is not fixed in the retaining structures, then ground anchors will produce angular bending or loss of function, and may cause serious damage. It is recommended that the bearing plate and trumpet be welded and put together with the embedded hole pipe, to avoid angle offset and produce angular bending after the anchor stressing.

(5) Detecting the function of the existing ground anchors and providing reinforcement is imperative at this stage. Using visual inspection, endoscopic detection instrument and lift-off test methods to detect degradation is recommended. Anti-corrosion methods and load measurement after the lift-off test is completed, in addition to the anchor load cell is recommended, to monitor the change of ground anchor force, thus ensuring the safety of the retaining structure.

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