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Deterioration model of ground anchor for slope stability assessment

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ABSTRACT

There is a ground anchor technique as one of the earth reinforcements to sustain the stability of the slope, which has been widely used for stabilizing cut slopes in Japan for the last thirty years. As ground anchors are anticipated to be deteriorated by geological environments such as ground water and natural disasters such as earthquake and typhoon, it is recommended to evaluate its performance by regular survey and tests. Moreover, it is believed that old-type anchors have a low protection performance against the corrosion on the surface of old-type anchors. Consequently, it is necessary to evaluate appropriately the damage of anchors as well as the stability of slope reinforced by deteriorated ground anchors. The performance of ground anchors is generally checked by soundness diagnosis, which is the visual check of anchor head, and lift-off tests, which is the loading test to measure a residual stress in anchor. The soundness diagnosis and lift-off test are effective for evaluating the performance of single anchor itself, however, the reliability of the safety assessment between the entire reinforced slope and the performance evaluation for single ground anchor has been questioned. This paper analyzed the reliability of soundness diagnosis based on the past regular surveys and lift-off tests statistically, proposed a deterioration model for single ground anchor using the Weibull distribution and finally assess the stability of reinforced slope with the proposed model.

Keywords: ground anchors, soundness diagnosis, Weibull distribution, deterioration model, stability assessment

1. INTRODUCTION

Ground anchor (hereinafter anchor), which was used in the construction of the Tomei Expressway in 1967 for the first time in Japan, has been used to sustain the stability of cut slopes and landslides. The deterioration of the old-type anchor due to corrosion is currently becoming noticeable, which induced the instability of slope reinforced with the old-type anchors. In the report "Technological Examination Committee on the long-term maintenance of highway assets and the way of replacement"¹⁾ summarized on January 2014, there is a proposal suggesting that the large-scale replacement of existing old-type anchors is necessary near future. Therefore it has become an urgent issue to evaluate the performance of the existing anchors considering its deterioration and suggest a replacement methodology in terms of the timing and location for maintaining the slope stability reinforced with anchors.

In this paper, we presented the statistical evaluation of soundness diagnosis of anchor based on the past visual surveys and lift-off tests, proposed a deterioration model for single ground anchor using the Weibull distribution and finally assess the stability of

slope reinforced with the proposed model.

2. THE DETERIORATION OF OLD-TYPE ANCHOR

The old-type anchor is a general term for the anchor that does not have a double corrosion protection while the new-type anchor, which has a double corrosion protection, has mainly used after 1990. As shown in Figure 1, the number of the old-type anchor is about 2.8 million, which is 67% of the total anchors in the

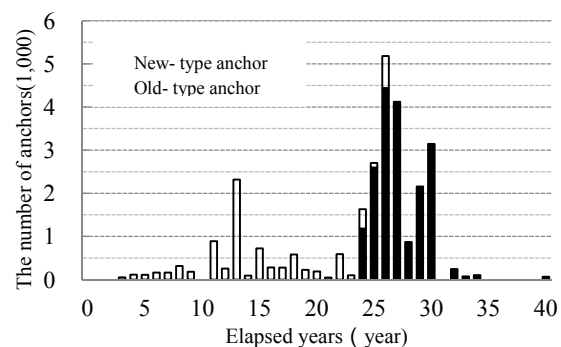
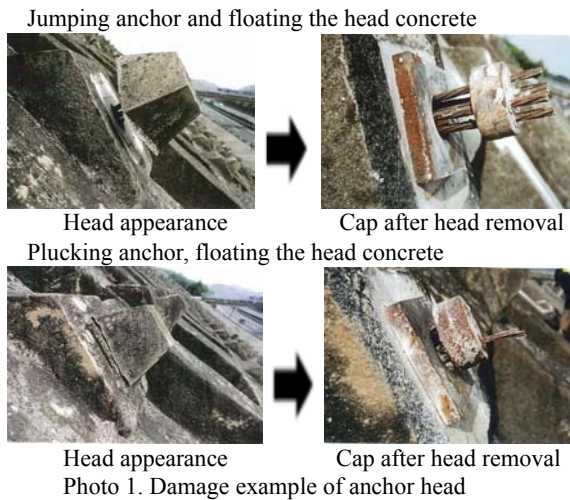


Figure 1. The number of anchors and elapsed years



Kyushu-Okinawa area, Japan. The average year elapsed after construction is more than 27 years. Although the head of old-type anchor is generally protected by concrete, the damage and failure of anchor occurred due to clogging of aggregate and mortar, slip between the wedge and anchor and corrosion resulting from water penetration as shown in Photo 1. In order to check the performance of single anchor, a periodic visual survey and lift-off test for existing anchors have been carried out. However, the results have not fully interpreted and utilized for the purpose of maintaining the stability of the slope reinforced with anchors.

3. SOUNDNESS DIAGNOSIS OF OLD-TYPE ANCHOR

3.1 Visual survey and lift-off test

In this research, visual survey was carried out for 4030 lines of old-type anchor in 32 reinforced slopes while the lift-off test was carried out for 5 - 10 % of old-type anchors in 32 reinforced slopes on a random basis. The visual survey was mainly carried out through checking the jump of anchor and the float of anchor head. The lift-off test is an in-situ loading test to measure stress-strain curve of existing single anchor and obtain a residual tension stress in anchor. The damage rank of single anchor was defined as shown in

Table 2. The results of visual survey and lift-off test

Damage rank	Visual Survey (line)	Visual survey (%)	Lift-off Test (line)	Lift-off Test (%)
I	3,395	84.2	143	58.6
II	117	2.9	74	30.3
III	498	12.4	13	5.3
IV	18	0.4	3	1.2
V	2	0.0	11	4.5
Total	4,030	100.0	244	100.0

Table 1 based on the results of visual survey and lift-off test.

Table 2 shows the results of visual survey and lift-off test. The percentage of rank I through visual survey is very high compared to it through lift-off test, which is suggesting that the damage of anchor judging by visual survey tends to underestimate compared with the lift-off test. This is partly because the visual survey of anchor depends on the condition of anchor head and the abnormality of underground anchor part is not easily found only by visual survey. In general, however, the lift-off test is carried out only for about 5 to 10% of all anchors²⁾ because it is expensive and time-consuming test compared to visual survey. Therefore, in order to assess the stability of reinforced slope through visual survey, it is a challenge to eliminate the difference between visual survey and lift-off test.

3.2 Reliability evaluation of visual survey

Table 3 shows the comparison of the results from lift-off test and visual survey. "Damage detection rate" means the reliability of visual survey, which defines the number of damage rank from visual survey, colored area in Table 3, divided by the number from the lift-off test for a given rank. On the other hand, "failure potential" means the percentage of failure anchor, which defines the number of rank V, thick frame part in Table 3, divided by the total lines of 244. The damage detection rate for visual survey was 58.2% and the failure potential obtained from the lift-off test was 4.5%. As mentioned-above, the result from visual survey tends to underestimate the performance of anchor and the test number of lift-off test is limited. In order to

Table 1. Soundness diagnosis of anchor (damage rank and anchor condition)






Rank	:Failure	:The later acceleration period	:The first acceleration period	:Progress period	:Incubation period
Visual survey	 Jumping anchor	 Floating anchor /Significant rust	 Oil leaks/ Rust	 Slight oil leaks/Slight rust	 OK
Lift-off test	Anchor load; No lift-off load /Overstressing Peculiarity; Inelastic after lift-off load	Anchor load; Far and away exceeding the allowable limited Peculiarity; Inelastic after lift-off load	Anchor load; Under the allowable limited Peculiarity; Elastic before predetermined load after lift-off	Anchor load; Within the allowable limited Peculiarity; Abnormal partly in elastic modulus	Anchor load; OK Peculiarity; OK

Table 3. The comparison of the lift-off test and visual survey (lines)

		Lift-off test					Total
Visual survey		65	79	9	1	7	161
		7	4	0	0	0	11
		30	31	4	2	4	71
		1	0	0	0	0	1
		-	-	-	-	-	0
	Total		103	114	13	3	11

estimate reliable failure potential for all anchors, the failure potential R with 95 % currency is calculated by the following formula (1)

$$r - 1.96 \sqrt{r \cdot \frac{1-r}{n}} \leq R \leq r + 1.96 \sqrt{r \cdot \frac{1-r}{n}} \quad (1)$$

where, r is failure potential obtained from the lift-off test and n is the number of lift-off test. In this study, 1.9% R 7.1% is obtained.

4. DETERIORATION MODEL OF ANCHOR

There are multi-stage analysis and binary analysis to express a typical deterioration of anchor. It is reported that multi-stage analysis underestimates the anchor deterioration because Markov process, a constant transition probability, is assumed in the multi-stage analysis³⁾. In order to assess the current stability of existing slope reinforced with anchors considering its deterioration at the same time, the performance of existing anchors, namely the failure percentage of anchors, is expressed by the Weibull distribution.

The anchor failure percentage $F(t)$ is expressed by Formula (2) of Weibull distribution⁴⁾, and Mean time to failure $MTTF$ is expressed by Formula (3).

$$F(t) = 1 - \exp\left\{-\left(\frac{t}{\eta}\right)^m\right\} \quad (2)$$

$$MTTF = \eta \cdot \Gamma\left(\frac{1}{m} + 1\right) \quad (3)$$

where, scale parameter m and shape parameter η are Weibull coefficient, and $\Gamma(\cdot)$ is Gamma function.

Figure 2 shows Weibull plot for the threshold ranks of V and II in lift-off test respectively. It is noted that the threshold rank is the damage rank when anchor regards as in failure condition. In the case for the threshold of V, $m = 5.16$, $\eta = 47.5$ and $MTTF = 43.7$ while $m = 5.70$, $\eta = 47.5$ and $MTTF = 29.0$ for II. It could be seen that Weibull plot moves to the big side of the time axis as the threshold rank increases, which is suggesting that the elapsed time to reach failure condition increases as the threshold rank become large. Also, it is shown that relationship between the elapsed years with the failure percentage of anchor can be quantitatively evaluated with the Weibull distribution.

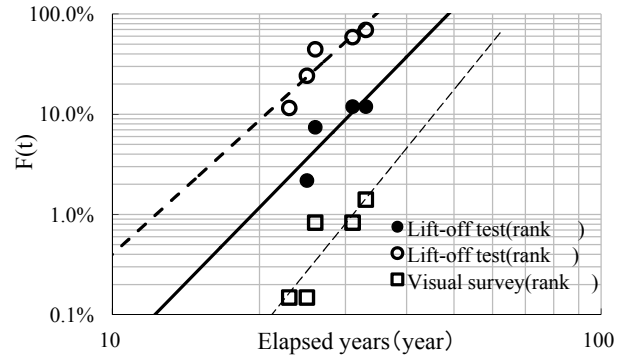


Figure 2. Weibull plot about determination division

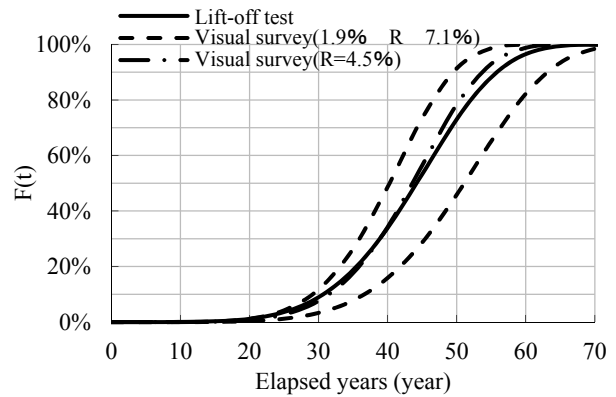


Figure 3. Failure prediction of lift-off test and visual survey

Weibull plot from visual survey for the threshold rank of V is shown in Figure 2, which indicates that $m = 6.03$, $\eta = 66.7$, $MTTF = 61.8$. The failure percentage from visual survey is low than that from lift-off test. In order to improve the accuracy of visual survey, it is necessary to consider the reliability of visual survey and correct the failure percentage by visual survey.

Figure 3 and Table 4 show the correction methodology for the failure percentage by visual survey. As shown in Table 4, the failure percentage by visual survey was corrected by multiplying "failure rate potential" explained in section 3.3 and Table 3. The failure percentage through lift-off test was located in the estimated range with 1.9% R 7.1%, and was approximated to the failure percentage through visual survey corrected by $R = 4.5\%$ ($m = 5.79$, $\eta = 46.5$, $MTTF = 43.0$). It means that it was possible to improve the accuracy of failure percentage through visual survey with reliability estimation.

Figure 4 shows the relationship between the failure percentage of anchor and the number of anchor for nine slopes that the replacing anchor was performed in past. It is shown that existing anchor needs to replace when failure percentage roughly reaches from 4 to 10%. In previous studies⁶⁾, it is also reported that replacing of anchors is necessary until about 17% of anchor lose their function. It can be concluded that the existing

Table 4. Estimation by cumulative hazard method⁵⁾ through visual survey($R=4.5\%$)

Elapsed years (year)	Visual Survey (line)	Determination Division " " (line)	Applicable Non-failure (line)	Failure Potential (line)	Corrected failure (line)	Cumulative hazard estimate ($H(t)$)
23	939	2	4,030	42	44	0.011
25	1,193	0	3,091	54	54	0.028
26	1,659	0	1,898	75	75	0.068
31	68	0	239	3	3	0.080
33	171	0	171	8	8	0.125
Total	4,030	2	-	182	184	-

anchor needs to start replacing when the failure percentage of anchor reaches from 10 to 20%. Moreover, it is able to assess the current slope stability reinforced with anchors by considering the failure percentage such as Figure 3 and also estimate the timing and priority for replacing anchor by comparing the stability of reinforced slopes.

5. SUMMARY

This paper analyzed the reliability of soundness diagnosis based on the past regular surveys and lift-off tests statistically, proposed a deterioration model for single ground anchor using the Weibull distribution and finally assess the stability of reinforced slope with the proposed model. The main conclusions are as follows:

1) The failure percentage of existing ground anchors can be estimated by using the Weibull analysis through lift-off test by cumulative hazard method.

2) It was found that result from visual survey underestimates the performance of ground anchor. The evaluation method to correct the failure potential of ground anchor was proposed. The failure potential obtained from this study is estimated that 1.9% R

7.1%, which can be used in correcting the accuracy of visual survey.

3) When the failure percentage of anchor reached to about 20%, the need for replacing anchor increases.

4) It is possible to propose an appropriate timing for replacing anchor and priority for reinforced slope by using 1), 2) and 3).

The results of visual survey and lift-off test used for this study such as transition time to reach each damage rank is not measured. In addition, the visual survey and lift-off test were carried out within about 10 years and the variation of the sampling period was treated as a random censored data to determine the failure percentage of anchors. In the next study, the proposed deterioration model for ground anchor should be revised by collecting further data. In addition, in order to set proper the threshold damage rank of anchor, we want to create a sample replacement model of the reinforced slope.

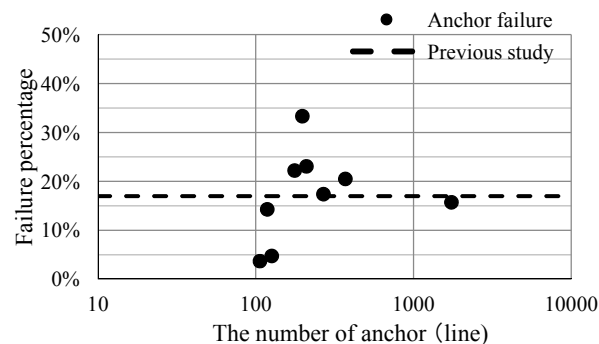


Figure 4. Realities of anchor damage to the time of the renewal measures

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